Report No. CG-D-06-95

Free Running Model Turning Tests of the U.S. Coast Guard 47 FT Motor Life Boat

Edward M. Lewandowski

Davidson Laboratory
Stevens Institute of Technology
711 Hudson Street
Hoboken, NJ 07030

FINAL REPORT
FEBRUARY 1995

This document is available to the U.S. public through the National Technical Information Service, Springfield, Virginia 22161

Prepared for:

U.S. Coast Guard
Research and Development Center
1082 Shennecossett Road
Groton, CT 06340-6096

and

U.S. Department Of Transportation
United States Coast Guard
Office of Engineering, Logistics, and Development
Washington, DC 20593-0001

NOTICE

This document is disseminated under the sponsorship of the Department of Transportation in the interest of information exchange. The United States Government assumes no liability for its contents or use thereof.

The United States Government does not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report.

The contents of this report reflect the views of the Coast Guard Research & Development Center. This report does not constitute a standard, specification, or regulation.

W. E. Colburn, Jr.
Technical Director, Acting
United States Coast Guard
Research & Development Center
1082 Shennecossett Road
Groton, CT 06340-6096

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
CG-D-06-95		

4. Title and Subtitle

Free Running Model Turning Tests of the U.S. Coast Guard
47 FT Motor Life Boat

5. Report Date
February 1995

6. Performing Organization Code

7. Author(s)
Edward M. Lewandowski

8. Performing Organization Report No.
R&DC 20/93

9. Performing Organization Name and Address

Davidson Laboratory
Stevens Institute of Technology
711 Hudson Street
Hoboken, NJ 07030

10. Work Unit No. (TRAIS)

11. Contract or Grant No.
DTCG23-92-D-E01032

13. Type of Report and Period Covered
Final Report

12. Sponsoring Agency Name and Address

U.S. Coast Guard
Research and Development Center
1082 Shennecossett Road
Groton, Connecticut 06340-6096

Department of Transportation
U.S. Coast Guard
Office of Engineering, Logistics, and Development
Washington, D.C. 20593-0001

14. Sponsoring Agency Code

15. Supplementary Notes

Coast Guard R&D Center COTR: James A. White, 203-441-2734.

16. Abstract

Free running, radio-controlled, turning tests were performed on a 1/9 scale, self-propelled model of the USCG 47 FT Motor Life Boat (MLB) in order to study the roll characteristics of the boat in turn. Preliminary captive model tests were first carried out on a straight course in a towing tank to calibrate throttle settings and to check rudder effectiveness. Underwater photographs were taken. Little or no ventilation was observed on the rudders.

Free running turning tests were then conducted in a maneuvering basin. The model was outfitted with running lights and a visual roll angle display. Overhead photographs were taken and analyzed to obtain trajectory coordinates, and the roll angle, drift angle and heading of the boat as a function of time. Tests were run at scaled speeds corresponding to 10 and 27 knots, rudder angles of 20 and 30 degrees and scaled rudder rates of 5 and 10 degrees per second. Significant differences were measured between the turning parameters at 10 knots and 27 knots. Less significant differences were measured at the two different rudder rates. All results are presented in both tabular and graphical form.

17. Key Words

Motor Life Boat
Turning
Roll
Maneuvering
Stability
Planing Boats

18. Distribution Statement

Document is available to the U.S. public through the National Technical Information Service, Springfield, Virginia 22161

19. Security Classif. (of this report)	20. SECURITY CLASSIF. (of this page)	21. No. of Pages	22. Price
UNCLASSIFIED	UNCLASSIFIED		

Form DOT F 1700.7 (8/72) Reproduction of form and completed page is authorized

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (WEIGHT)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (EXACT)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly).

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (WEIGHT)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	0.125	cups	c
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (EXACT)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F

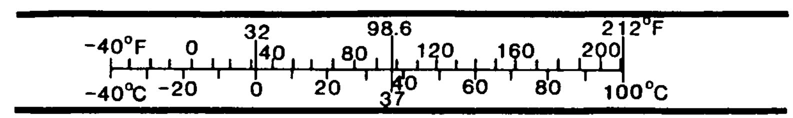


TABLE OF CONTENTS

INTRODUCTION

The initial configuration of the prototype 47 ft Motor Life Boat experienced large transient roll angles while in the initial phase of high-speed, large rudder angle turns. The transient was of short duration, and has been characterized as a "snap roll" phenomenon. To demonstrate that such phenomena can be accurately reproduced using a 5 ft model, a self-propelled, radio-controlled model of this craft was designed, built and tested. Preliminary captive tests were conducted in the High Speed Test Facility at the Davidson Laboratory in March and April, 1993. Free running model tests were conducted in the Maneuvering and Seakeeping Basin at Davidson Lab in April and May, 1993. Most of the free-running tests and some of the captive tests were witnessed by Mr. James White of the US Coast Guard. A portion of the free-running test program was witnessed by Mr. Daniel Bagnell of Band, Lavis and Associates, and by Mr. Walter Lincoln of the US Coast Guard.

MODEL

A model of the 47 ft MLB was fabricated from wood according to USCG Drawing 47 MLB-801-001 C, to a scale of 1/9.032. The scale was chosen in order to make use of stock propellers (Davidson Laboratory #80, Diameter = 0.258 ft). Rudders were fabricated from Lexan according to USCG Drawing 47 MLB-562-010. Brass shaft struts and barrels were fabricated according to USCG Drawing 47 MLB-161-010 B. Mylar strips were placed long the upper chine of the model from bow to stern, extending 1/32 in. (model-scale) below the chine, to provide a sharp edge. The model is shown on Figure 1, which also gives principal dimensions.

A preliminary powering study indicated that an electric motor would not be a satisfactory propulsor because of weight considerations. Thus, an internal combustion motor (O.S. Engines model FS-91, rated at 1.6 BHP @ 11,000 rpm) was chosen. A gearbox was designed and built for the two counterrotating shafts, with a 2:1 reduction. Therefore, both propellers always rotated at the same RPM. The model was outfitted with a Davidson Laboratory receiver and servos to control the throttle and choke (which was used to cut the engine).

A small electric motor was used to drive the rudders through a gear assembly. A circuit was designed to run the motor at two preset adjustable speeds, which were set to 5 and 10 deg/sec full-scale at the rudder stocks. A series of cams were installed on the shaft of the rudder motor, with detents corresponding to rudder angles of 20 and 30 degrees. Microswitches were used in conjunction with the cams to stop the rudders at the desired angle. After the preliminary captive tests, in which large roll angles were observed, the model sides were extended upward to an approximately uniform height of 5 in. model-scale above the afterbody deck.

Ballasting

For setting the CG of the model, pegs were temporarily fastened to the hull of the model. The pegs were attached at the specified full-scale CG, and protruded approximately 1.5 in. from the hull. The pegs were shimmed so that they were perpendicular to the longitudinal centerplane of the model. The model was then placed between two metal blocks, with the pegs resting on the blocks, so that it was free to pivot through 360 degrees. Ballast weights and moveable equipment were then shifted within the model until the CG was at the pivot point. It was noted that this method seemed to be extremely precise, as an applied moment of as little as .005 ft-lb (corresponding to a CG change of roughly 0.0001 ft model scale) caused the model to rotate.

Yaw gyradius was checked by use of the bifilar pendulum method. The model was suspended horizontally using two long steel cables, attached to the model at equal distances ahead of and aft of the CG. Small amplitude yaw oscillations about the CG were then set up and the period measured with a stopwatch. The period of yaw oscillation is related to yaw gyradius as follows:

$$T=\frac{2\pi k\sqrt{L/g}}{a}$$

where T is the period, k is the yaw gyradius; L is the length of the steel cables, and 2a is the distance between the cables. Preliminary tests indicated that the yaw gyradius was too large; the motor was then moved back and electronic equipment moved up to achieve the lowest possible value (see Table 1). The virtual roll moment of inertia was determined from the results of a roll decay test. The virtual roll inertia is related to the roll period as follows:

$$T=2\pi\sqrt{\frac{I_{xx}'}{W\cdot GM}}$$

where I_{xx}' is the virtual roll inertia, W is the displacement, and GM is the metacentric height. The roll period was measured with a high degree of precision using a recording oscilloscope connected to the output of the gyroscope which was mounted in the model (the gyro is described in the next section).

An inclining test was conducted prior to the captive straight-course tests. Results are shown on Figure 2. The inertial properties of the model, and corresponding target values, are listed in Table 1. All quantities are within specified limits except for yaw gyradius, which was 3.4% high. A small fuel tank (weight = 0.45 lb full) was used, placed as close as possible to the CG of the model to minimize any possible effect of fuel consumption on inertial properties.

APPARATUS AND INSTRUMENTATION

Captive straight-course tests were carried out in the High Speed Test Basin, which is 313 ft long, 12 ft wide, and 5.5 ft deep. The model was towed free to trim and heave (but fixed in surge, sway and yaw) from a point on the propeller shaft line at the LCG, 0.48 ft aft of Station 6 and 2.26 ft above the baseline (dimensions will be given in full-scale unless otherwise noted). Some of the tests were conducted free to roll; a roll pivot box, instrumented to measure roll angle, was mounted above the pitch pivot box for this purpose. The roll pivot was 5.01 ft (99.4% of KG) above the baseline. The rudders were manually operated during these tests; a large protractor on the port rudder shaft was used to set the angle (the two rudders were geared together, as in the later free-running tests). A drag balance, located between the pivot box assembly and the free-to-heave mast, was used to measure net resistance. A tachometer fixed to the port propeller shaft forward of the gearbox was used to monitor engine speed.

All signals were monitored during the test using an oscillograph chart recorder. Figure 3 is a photograph of the model in the rudder effectiveness test rig. A Futaba 4 channel AM radio transmitter/receiver set was used to control the speed (throttle), choke (engine cutoff) and (in the free-running tests) rudder motion. For throttle control, the joystick on the transmitter was replaced by a 10-turn potentiometer, permitting more precise speed settings. For the free-running tests, the pivot boxes were removed and replaced by a gyroscope. To provide power for the gyro (24 volts

DC), two 12-volt battery packs were installed. The analog output of the gyro is a voltage which is linearly proportional to roll angle (0 to 60 deg). An on-board Motorola 6811 8-bit single chip microprocessor was used to digitize the voltage, multiply by a calibration factor, and send the output to a large 3-digit LED display, strobed at 5 Hz with a duration of 1 ms. The first digit of the roll display gave the sign of the roll angle and the second and third digits gave the roll angle to the nearest degree.

The model was also outfitted with running lights at the bow and stern (red light at the bow; green at the stern) which were on continuously during the tests and pulsed at high intensity in synchronization with the roll angle display; the LCG is located at the upper transverse bar of the 10's digit of the roll display. A third LED (yellow) was located on a small "tiller" on the rudder motor, to be used as an indicator of rudder action. The on-board instrumentation is shown on Figure 4. Locations of the running lights are also given on Figure 4. The fully equipped free-running model is shown at rest on Figure 5a and running at 27 knots on Figure 5b. Tests were conducted in the Maneuvering and Seakeeping Basin at Davidson Laboratory, which is 75 ft square with a water depth of 4.5 ft. The room was darkened by covering the windows with aluminum foil. Overhead photographs were taken using two Hasselblad EL cameras with Distagon 40 mm lenses; the aperture setting was f4. The cameras were located 16 ft above the water surface, above the southwest and southeast quadrants of the basin. Figure 6 is a plan view of the basin, showing the camera locations and the platform from which the model was launched. Kodak Vericolor ASA 400 color film was used, which was "pushed" in processing two stops to ASA 1600. The cameras were connected to a common trigger button which was located at tankside near the launch area. The cameras were adaptable to Polaroid film by switching backs; thus preliminary tests could be done using Polaroid film prior to loading the regular film.

TEST PROGRAM AND PROCEDURE

Straight-course Captive Tests

Captive tests were carried out on straight-course to calibrate the model speed vs transmitter throttle setting, to determine the steady state zero yaw rudder effectiveness, and to check for ventilation of the rudder surfaces. For the throttle calibration tests, the model was towed at speeds of 10 and 27 knots with the motor running. A range of throttle settings (and thus engine RPM's) was run at each speed. In addition, a number of repeat runs was carried out at various throttle settings. The test procedure was first to take zero readings on the drag and RPM transducers with the model floating and at rest, and the motor off. Next, the throttle potentiometer was set to the desired value, and the motor started. Finally, the carriage was towed down the tank at the specified speed (10 or 27 knots). Resistance and RPM readings were acquired in a 50 ft data trap, after the model had reached steady speed and RPM. The running readings less the corresponding zeroes constitute the measured values for each run. An attempt was made to "zero in" on the throttle setting which resulted in a balance of thrust and drag (zero net resistance) and to assess the repeatability of the speed at that setting.

To examine rudder-induced roll behavior on straight course, a series of tests was conducted with the model towed free to roll (in addition to being free to heave and trim). For these tests, the roll locking clamp was removed from the roll pivot box. The test procedure was the same as that described above, with the exception that the rudder angle was set to the desired angle prior to each run, and that zeroes and running readings of roll angle were recorded in addition to drag and RPM; also, underwater running photographs were taken of the stern region of the model to check for ventilation. Tests were conducted at speeds of 10 and 27 knots, at a single throttle setting appropriate for each speed at zero rudder deflection. At 10 knots, tests were conducted at rudder angles of -30, -20, -10, 0, 10, 20, 25 and 30 degrees; positive rudder angles correspond to clockwise rotation about the rudder shaft, looking down. At 27 knots, tests were run at -15, -10, 0 and 10 degrees; higher rudder angles were not run because of the large roll angle (36 degrees) experienced at the rudder angle of -15 degrees which resulted in water above the lower deck edge. Prior to the free-running model tests, some problems were encountered with the model engine, necessitating removal and cleaning of the carburetor.

To check the speed calibration, runs were made straight across the Maneuvering and Seakeeping basin at a range of throttle settings. Overhead Polaroid photographs were taken, and speed determined using a "calibration photo" of an object of known length. These and other preliminary "practice tests" showed that the model tracked straight at zero rudder angle, and that it reached steady speed very quickly (practically instantaneous at 10 knots; within 15 ft of launch from zero speed at 27 knots). Unfortunately one of these calibration tests resulted in a head-on collision of the model with a tank wall at high speed, resulting in a large vertical crack in the model extending from the deck to just above the upper chine. This was quickly repaired and no subsequent problems (such as leakage) were noted.

For the tests, the model was launched from a platform at the northwest corner of the Maneuvering and Seakeeping Basin. All lights were extinguished except for three fluorescent fixtures along the north edge of the tank; these were found to not adversely affect the quality of the photographs. The throttle was set to the appropriate point, and the motor started. Observers were stationed around the perimeter of the tank to prevent a collision with the walls. After starting the motor, the model was manually held using a handle on the transom while the gyro and flashing display were powered up. The model was then aimed parallel to the west tank wall (it was later found to be more effective to aim at the southwest corner of the basin) and released; the model was given a "push" at the start of the 27 knot runs to aid in reaching speed quickly. The camera shutters were opened manually at launch and held on "time" until the model was stopped due to proximity of a wall, or until a complete turn was negotiated. The motor was cut when it became apparent that the model would otherwise strike a tank wall, however at 10 knots and at some conditions at 27 knots, a full turn could be made.

Free-running tests were conducted at speeds of 10 and 27 knots, rudder angles of -20 and -30 degrees, and at rudder rates of 5 and 10 degrees/second. Rudder action was initiated at various points in the tank in an attempt to capture all phases of the turns on at least one of the two cameras. In the first test session, twelve rolls of 12-exposure film were shot during these tests, of which 90 photographs were found to contain sufficient information for processing. Color 8 x 8 inch prints of these 90 negatives were made. All negatives were marked with film roll and shot number immediately after processing.

Preliminary analysis of the prints indicated that the approach phase of the trajectory was not visible on any photograph for three of the four conditions at 27 knots. Thus, additional tests were conducted in which the model was launched from the west end of the tank, parallel to the south wall, so that the approach phase would be recorded by the southwest camera. Twelve runs were made, consuming an additional two rolls of film (one per camera). Twenty-two additional 8 x 8 prints were made from the negatives.

RESULTS

Results of the throttle calibration tests are given in Table 2, which lists run number, nominal boat speed in knots, actual model speed (fps), potentiometer setting, shaft speed (model RPM), and net resistance (lb, model). The results of runs 1-173 have not been included in the table as they were conducted with a motor which overheated and had to be replaced (with an identical model, which seemed to perform better). Net resistance is plotted as a function of propeller RPM on Figures 7 and 8, and as a function of throttle setting on Figures 9 and 10, for speeds of 10 and 27 knots, respectively. The throttle potentiometer units are arbitrary, with a setting of 12.60 corresponding to closed and 16.90 corresponding to wide open.

Results of the rudder effectiveness test are given in Tables 3.1 and 3.2, for speeds of 10 and 27 knots, respectively. The tables list run number, rudder angle, roll angle, model speed (fps), propeller RPM (model), and net resistance (model lb). Roll angle is plotted against rudder angle on Figures 11 and 12 for speeds of 10 and 27 knots, respectively. Underwater photographs revealed no evidence of ventilation except possibly at a speed of 10 knots and a rudder angle of 30 degrees, where a few isolated air bubbles could be seen on the low pressure side of the port rudder. A set of the underwater photographs has been delivered to Mr. White of the Coast Guard at his request.

Results of the free-running model tests, from analysis of the overhead photographs, are presented in Tables 4-7 for the approach speed of 10 knots and in Tables 8-11 for the approach speed of 27 knots. The tables list time in seconds; x and y coordinates of the CG in feet; and heading, roll and drift angles in degrees; these quantities are defined on Figure 13. Steady-state turning qualities are tabulated in Table 12, which lists advance, transfer, and tactical diameter in feet for each test condition. Steady-state turning parameters are defined on Figure 14. The tabulated quantities were determined by the method described under Analysis below.

Trajectories at 10 knots are shown on Figures 15 and 16, and time histories of heading, roll and drift angles are plotted in Figures 17 - 21. Trajectories for the approach speed of 27 knots are shown on Figures 22 and 23, and the corresponding time histories of heading, roll and drift appear on Figures 24 - 27. Figures 24a - 27a show an expansion of the first eight seconds of the maneuvers depicted in the corresponding Figures 24 - 27. Figures 24a - 27a also show the rudder angle; the rudder angles are shown negative (they are positive according to the sign convention defined above). The time of rudder execution was taken to be at 0 seconds on these figures; the actual instant of rudder execution is not precisely known as discussed below.

ANALYSIS

Analysis of the overhead photographs to determine the trajectories of the 47 ft MLB was carried out in four basic steps, as described below:

1. Assemble photographs

The first step in the analysis was to sort the photographs by condition (speed, rudder angle, rudder rate). As the camera field was limited to a 20 ft x 20 ft area, a complete turn could not be photographed on a single negative. Photographs covering various phases of the turns were obtained by launching from several locations in the tank and throwing the rudder at different times as described under Test Procedure above. Thus as many as 30 photographs were obtained for each condition. The photographs were carefully examined to find those which best showed the various portions of the trajectories. These prints were then joined together to form the complete trajectory. The photographs were joined by visually matching the curvature of the trajectories of the bow and stern lights, and by matching the roll angles as indicated by the display. As few as three photographs were required to obtain a complete picture of a turn at low speed, whereas many as 7 were assembled for a high-speed case (with a considerable amount of "overlap").

2. Measurement

A large transparent grid was prepared for measurement of the coordinates of the model from the photographs. The grid had 0.05 in. graduations permitting measurements to the nearest 0.025 in. The x (advance) axis of the grid was aligned with the trajectory of the model CG in the approach (straight line) portion of the turn. The origin was chosen to coincide with the model CG one time step (0.2 sec model-scale) before any apparent deviation (in heading, drift or transfer) from the initial straight trajectory. The rudder indicator light (yellow LED) was not useful for determining the rudder position because the yellow trace did not show well on the photographs, and because roll motion caused an apparent displacement of this light because it was not in the same horizontal plane as the bow and stern lights. Thus it was not possible to determine the time of rudder execution. However it is expected that the coordinate system described above will permit a valid comparison among the conditions examined.

Using the grid, the coordinates of the model CG, indicated by the forward transverse bar of the roll LED display, were recorded. Coordinates were recorded at each pulse (0.2 sec) for the high-speed runs, and at every other pulse for the low speed runs. Next, a transparent protractor was used with the grid to measure the heading angle between the longitudinal axis of the boat and the initial course (x-direction); the protractor permitted measurement to the nearest 0.5 degree.

Finally, the drift angle was measured at each time step (alternate time steps at low speed). To do this, the local radius of curvature was found by fitting a circle to the trajectory of the CG in the vicinity of the point of interest, using a transparent circle template. The angle between a normal to the radial line passing through the CG, at the CG, and the longitudinal axis of the model determines the drift angle, as shown on Figure 13. The roll angle was simply read (to the nearest degree) from the LED display.

3. Determination of Scale

The scale of the photographs was determined by measuring the distance between the bow and stern lights using a digital caliper. It was determined that the scale was not constant on each photograph, presumably due to distortion produced by the lens. After some investigation it was found that the photographic image became consistently smaller as the model progressed from right to left across the field of view, typically ranging from 2.0 in. at the lower right corner of a print to 2.15 in. at the upper left corner. To correct for this distortion, the length of the first and last image used on each photograph was recorded. Then, a scale factor for each time step was computed assuming a linear variation across the photograph. The scale factors were used to compute new x and y coordinates at each time step. No corrections were applied to the drift and heading measurements, which were not expected to be significantly affected by distortion.

4. Final adjustments

Further analysis of the corrected trajectory data showed that in the photographs obtained in the second test session, showing the approach phase of the turns, the model was not up to speed when the turns were initiated. This affects the measured advance but has little effect on other quantities since transfer, heading, drift and roll were all small in this phase of the turn. Unfortunately it was not feasible to conduct additional tests when this deficiency was discovered. Thus a further correction was applied as described in Appendix A. It is emphasized that this second correction most strongly affects the x-coordinates in the trajectories and thus has little influence on key parameters such as transfer and tactical diameter.

At an approach speed of 27 knots and a rudder deflection of 30 degrees, the tactical diameter could not be determined directly from the photographs because of insufficient length of the trajectory. In this case the tactical diameter was estimated by assuming a steady speed and rate of heading change from the end of the measured trajectory.

DISCUSSION

Captive Straight Course Tests

The salient feature of the results of the throttle calibration tests was the amount of scatter in the RPM obtained for a given transmitter setting. It was thought that inconsistent fuel flow was partially responsible; two types of fuel pumps were tried, as well as raising the fuel tank, all with little effect. It was noticed, however, that after a warm up period, the behavior was much more consistent than in the initial runs during any test period.

After some preliminary tests, two steel flywheels were fabricated and attached to the front of the motor to improve low RPM performance and to help the motor to come to a more gradual halt when stopped. Prior to installation of the flywheels, the engine stopped so abruptly that a propeller shaft coupling broke; also it could not be run at the low RPM's required for 10 knots. The flywheels greatly improved the performance of the engine.

The free-to-roll tests conducted at 10 knots showed a nearly linear variation of roll angle with rudder deflection in the range of rudder angles from -30 to +20 degrees. Some loss of rudder effectiveness is apparent at +25 and +30 degrees; the reason for the asymmetry (no loss of effectiveness at -30 degrees) is unknown.

As the model came up to speed for the first free to roll run at 27 knots with nonzero rudder angle (+10 degrees was run), the roll angle of the model very rapidly reached its final value of -27 degrees; the model deck was then dangerously close to the water surface on the port side. This happened too quickly for the drive operator (the author) to stop the carriage; fortunately the equilibrium roll angle was not large enough to swamp the model, and there was little (if any) roll overshoot. For subsequent runs, a mylar sheet, extending 3 1/2 inches above the model deck, was fastened to the model. A roll angle of 36.26 degrees was measured at a rudder deflection of -15 degrees; higher rudder angles were not attempted.

It is noted that in a turn, the angle of attack of the rudders is reduced by the drift angle and angular velocity of the craft; thus such large roll angles at moderate rudder deflections are not expected. The absence of roll overshoot in the straight-course tests is probably related to the test procedure: the model was brought up to speed with the rudders deflected, resulting in a relatively gradual buildup of rudder force.

Free-Running Tests

One of the most striking results of the free-running tests is the large difference in turning diameter at the two test speeds. Figures 28 and 29 show a comparison of the trajectories at rudder angles of 30 and 20 degrees, respectively. This is quite different from the performance of displacement ships, for which tactical diameter is virtually independent of approach speed. At the approach speed of 10 knots and a rudder angle of 30 degrees the turning diameter of the 47 ft MLB is just under 4 boat lengths, which is slightly inferior to what one would expect of a typical displacement ship (reference 2). The corresponding diameter at an approach speed of 27 knots is about 8.7 boat lengths.

The reason that the turning diameter of a displacement ship is nearly independent of approach speed is that both the required centripetal force and the hydrodynamic forces and moments on the ship are proportional to the square of the ship's velocity. This is apparently not the case for planing craft. In addition, the roll motion of the 47 ft MLB at 27 knots is significant, whereas the roll motion of displacement ships in turns is often neglected. Thus maneuvering standards applicable to displacement ships, which do not consider speed or roll effects, would appear to be inappropriate for planing craft.

At the higher speed of 27 knots, a "snap-roll" phenomenon was indeed observed, in which the boat would initially roll into the turn to as much as 34 degrees, and then abruptly return to a lower roll angle of about 18 degrees; the turning diameter would become much wider at this point. After several seconds at the lower roll angle, there was a tendency for the roll to increase again; subsequent readings as high as 28 degrees were noted. In the initial transient, a large plume of water was noticed, emanating from the outboard propeller; it is possible that this propeller and the outboard rudder are losing effectiveness at the large roll angles, due to the proximity of the free surface, inducing the observed "flattening out" of the turn. Such a tendency was not observed in the straight-course tests; however the combination of turning and drift may bring the propellers closer to the surface than was the case on straight-course.

The effect of rudder rate on roll angle at high speed is shown on Figures 30 and 31 for rudder angles of 20 and 30 degrees, respectively. It an be seen that at the higher rate, the roll angle reaches a peak sooner (as expected) and that the peak is somewhat larger at the high rate. The oscillatory behavior mentioned above is evident here. The period of oscillation appears to be about 8 seconds which is larger than the natural roll period at zero speed, which was 3.05 seconds.

The time histories of the heading and roll of the craft on Figures 24 and 25 show that the rate of change of heading (turning rate) in the high speed turns increased in the initial phase of the turn until the time at which the maximum roll angle was reached, after which the turning rate steadied at a lower value (shallower slope on the figures). This is consistent with the observed "flattening out" of the turns mentioned above.

On six different runs, at 27 knots at a 20 degree rudder angle, the model was observed to turn through 90 degrees and then to rather abruptly stop turning, continuing in a straight line toward the tank wall. This happened five times at the slow rudder rate and once at the fast rudder rate. Photographs indicate that the drift angle and yaw rate approached zero, but that the roll angle held at about 20 degrees as the model approached straight-course. Subsequent equipment checks revealed no apparent problems. A satisfactory explanation for this phenomenon has yet to be found.

CONCLUDING REMARKS

This test program has successfully demonstrated that the "snap roll" phenomenon observed on the prototype 47 ft MLB could be duplicated at model scale; thus, the results of model studies can be applied with confidence to the investigation of such phenomena. It is strongly recommended that captive stability tests of the 47 ft MLB be carried out, and that the results be analyzed to provide further insight into the behavior of the craft. The present data can serve as a valuable check on the results of simulations which could be developed on the basis of the captive data; the simulator could then be applied to quickly assess the effects of simple geometry changes such as addition of skegs or changes in rudder geometry.

Comparisons of the present data to the turning performance of displacement ships indicate important differences: The roll behavior of planing craft can not be neglected, and the turning diameter at a particular rudder angle depends on speed, for example. It would thus appear that maneuvering standards which have been proposed for displacement ships should not be applied to planing craft.

REFERENCES

1. Mandel, P., "Ship Maneuvering and Control", chapter VIII in Principles of Naval Architecture, SNAME, 1967.

2. Barr, R.A., Miller, E.R., Ankudinov, V. and Lee, F.C. "Technical Basis for Maneuvering Standards", U.S. Coast Guard Report CG-M-8-81, December 1981.

TABLE 1 INERTIAL PROPERTIES

PROPERTY	TEST VALUE	TARGET VALUE
Displacement, lb	41,983a 41,972b	41,985* ± 840
LCG, ft aft of amidships	4.84	4.84 ± 0.10
VCG, ft above baseline	5.04	5.04
Virtual Roll Radius of Gyration, ft	5.77	5.75 ± 0.115
Yaw Gyradius, ft	11.10	10.73 ± 0.21
GM, ft	4.40	4.42 ± 0.09

Notes:

a Straight-course tests (basin temperature 71 deg F)
b Free-running tests (basin temperature 69 deg F)
* Seawater at 59 deg F assumed

TABLE 2 RESULTS OF SPEED CALIBRATION TESTS

Run no	Speed knots	Speed (model) fps	Pot. setting	Propeller RPM (model)	Net resistance lb (model)
174	27	15.12	14.20	4469	-0.77
175	27	15.17	14.20	4075	3.95
176	27	15.17	14.20	4103	3.50
177	27	15.17	14.20	4385	0.29
178	27	15.15	14.20	4377	0.51
179	27	15.17	14.20	4351	0.82
180	27	15.13	14.20	4344	0.90
181	27	15.17	14.20	4380	0.51
182	27	15.19	14.20	4374	0.63
183	27	15.15	14.20	4344	1.01
184	27	15.17	14.30	4454	-0.32
185	27	15.19	14.30	4448	-0.16
186	27	15.17	14.30	4443	-0.15
187	27	15.15	14.28	4451	-0.28
188	27	15.17	14.28	4453	-0.34
189	27	15.19	14.25	4449	-0.36
190	27	15.21	14.25	4459	-0.46
191	27	15.19	14.20	4385	0.38
192	27	15.15	14.22	4405	0.19
193	27	15.13	14.22	4417	-0.06
194	27	15.17	14.22	4418	0.02
195	27	15.13	14.22	4394	0.21
196	27	15.15	14.22	4404	0.17
197	27	15.13	14.22	4397	0.19
198	27	15.15	14.24	4410	0.06
199	27	15.17	14.24	4390	0.37
200	27	15.17	14.24	4396	0.17
201	27	15.19	14.24	4413	0.11
202	27	15.15	14.26	4424	-0.02
203	27	15.17	14.26	4420	0.03
204	27	15.21	14.26	4952	-0.34
205	27	15.17	14.26	4437	-0.10
206	10	5.60	13.40	2016	1.54
207	10	5.63	13.60	2514	-1.54
208	10	5.62	13.50	2430	-0.90
209	10	5.61	13.46	2168	0.90
210	10	5.61	13.48	2166	0.95
211	10	5.62	13.48	2232	0.42
212	10	5.61	13.48	2075	1.32
213	10	5.61	13.50	2290	0.13
214	10	5.62	13.50	2348	-0.29
215	10	5.62	13.50	2319	-0.18
216	10	5.62	13.50	2293	0.12
217	10	5.62	13.50	2334	-0.11
218	10	5.62	13.50	2403	-0.55

TABLE 3.1 RESULTS OF RUDDER EFFECTIVENESS TESTS
Speed: 10 knots

Run no	Rudder angle deg	Roll angle deg	Model speed fps	Prop RPM (model)	Net resistance lb (model)
85	0	-0.04	5.61	2188	-0.07
86	10	-2.73	5.61	2193	0.38
87	20	-6.11	5.59	2205	1.10
89	25	-6.56	5.59	2181	1.72
88	30	-5.26	5.58	2113	2.68
90	-10	2.85	5.60	2232	-0.44
91	-20	6.32	5.58	2213	0.70
92	-30	8.47	5.58	2225	2.04

TABLE 3.2 RESULTS OF RUDDER EFFECTIVENESS TESTS
Speed: 27 knots

Run no	Rudder angle deg	Roll angle deg	Model speed fps	Prop RPM (model)	Net resistance lb (model)
98	0	-1.50	15.15	4307	-0.60
100	0	-1.46	15.12	4251	0.31
101	10	-27.03	15.13	4248	2.30
102	-10	17.41	15.12	4341	-0.22
110	-10	17.61	15.15	4252	1.10
103	-15	36.26	15.12	4411	2.19

TABLE 4 Full-scale trajectory measured from overhead photographs.
Approach speed: 10 knots Rudder angle: 20 deg
Rudder rate: 10 deg/sec

Time sec	x ft	y ft	Heading angle deg	Roll angle deg	Drift angle deg
.0	.0	.0	-2.0	-2.0	.0
1.2	21.9	-.9	-6.0	-2.0	-2.0
2.4	43.8	-2.8	-10.5	-2.0	-3.0
3.6	64.3	-6.3	-16.0	-3.0	-4.5
4.8	84.2	-11.0	-23.5	-4.0	-6.5
6.0	102.4	-18.0	-32.0	-2.0	-7.0
7.2	119.1	-26.6	-39.5	-2.0	-8.5
8.4	134.4	-37.1	-47.5	-2.0	-9.0
9.6	148.1	-49.0	-54.5	-2.0	-10.0
10.8	159.9	-62.6	-62.5	-1.0	-9.5
12.0	169.5	-77.2	-70.0	-1.0	-9.0
13.2	177.3	-93.3	-78.0	-1.0	-9.5
14.4	182.9	-109.4	-85.0	-1.0	-10.0
15.6	186.3	-126.8	-92.0	-1.0	-9.5
16.8	187.5	-144.3	-99.5	-1.0	-9.5
18.0	186.3	-161.9	-106.5	-1.0	-9.5
19.2	182.2	-178.6	-113.5	-1.0	-8.5
20.4	176.8	-194.7	-121.0	-1.0	-8.5
21.6	169.1	-210.5	-127.5	-2.0	-8.0
22.8	159.1	-225.8	-136.0	-3.0	-9.5
24.0	146.2	-240.4	-144.0	-2.0	-8.5
25.2	131.5	-252.8	-151.5	-2.0	-8.5
26.4	115.4	-262.9	-159.0	-2.0	-8.0
27.6	97.9	-270.9	-167.0	-2.0	-8.0
28.9	79.8	-276.0	-175.5	-2.0	-8.0
30.1	61.1	-278.8	-184.0	-2.0	-8.5
31.3	42.4	-279.0	-192.5	-1.0	-9.0

TABLE 5 Full-scale trajectory measured from overhead photographs.
Approach speed: 10 knots Rudder angle: 20 deg
Rudder rate: 5 deg/sec

Time sec	x ft	y ft	Heading angle deg	Roll angle deg	Drift angle deg
.0	.0	.0	.0	.0	.0
1.2	22.6	.0	-.5	-1.0	-.5
2.4	44.5	-.2	-4.5	-1.0	-.5
3.6	65.9	-1.5	-9.5	-2.0	-3.0
4.8	86.5	-4.1	-15.0	-2.0	-5.0
6.0	106.5	-8.4	-21.0	-2.0	-6.5
7.2	125.4	-14.3	-28.5	-2.0	-8.0
8.4	142.9	-22.0	-36.5	-2.0	-8.0
9.6	158.5	-31.3	-44.0	-2.0	-8.0
10.8	172.3	-42.3	-51.0	-2.0	-8.0
12.0	185.1	-55.6	-59.0	-2.0	-9.0
13.2	196.0	-70.5	-67.5	-2.0	-9.0
14.4	204.3	-87.2	-75.0	-2.0	-8.5
15.6	209.7	-104.3	-83.0	-2.0	-8.0
16.8	214.8	-123.2	-91.0	-2.0	-8.5
18.0	216.0	-142.0	-98.5	-2.0	-8.0
19.2	214.6	-160.7	-106.0	-2.0	-8.0
20.4	210.2	-178.6	-112.5	-2.0	-8.0
21.6	204.1	-195.9	-120.0	-2.0	-7.0
22.8	195.7	-212.4	-128.0	-2.0	-7.0
24.0	184.9	-228.8	-136.5	-2.0	-8.0
25.2	172.3	-242.0	-145.0	-2.0	-8.0
26.4	157.4	-254.4	-153.0	-2.0	-8.5
27.6	141.3	-263.7	-160.5	-2.0	-8.5
28.9	123.8	-271.2	-168.5	-2.0	-8.5
30.1	105.4	-278.3	-178.0	-2.0	-9.5
31.3	86.9	-280.9	-185.0	-2.0	-11.0
32.5	68.7	-281.4	-193.0	-2.0	-11.0
33.7	50.6	-279.5	-200.5	-2.0	-10.5
34.9	33.5	-275.1	-208.5	-2.0	-10.0
36.1	16.6	-268.6	-216.0	-2.0	-11.0
37.3	1.0	-259.9	-223.0	-2.0	-10.0
38.5	-12.6	-249.7	-231.0	-2.0	-10.0
39.7	-25.2	-237.3	-238.0	-2.0	-10.0

TABLE 6 Full-scale trajectory measured from overhead photographs.
Approach speed: 10 knots Rudder angle: 30 deg
Rudder rate: 10 deg/sec

Time sec	x ft	y ft	Heading angle deg	Roll angle deg	Drift angle deg
.0	.0	.0	.0	.0	1.0
1.2	22.7	-.5	.0	-1.0	.0
2.4	45.2	-1.0	-4.0	-4.0	-2.0
3.6	67.4	-1.9	-11.5	-5.0	-6.5
4.8	87.9	-5.0	-21.5	-6.0	-11.0
6.0	107.2	-10.4	-33.5	-5.0	-11.0
7.2	124.0	-18.3	-43.0	-4.0	-11.5
8.4	138.6	-29.2	-54.0	-4.0	-10.0
9.6	148.2	-39.7	-66.0	-3.0	-10.0
10.8	158.1	-56.3	-77.5	-3.0	-11.0
12.0	163.9	-72.9	-89.5	-3.0	-11.0
13.2	166.1	-90.2	-100.0	-3.0	-12.0
14.4	165.4	-107.4	-110.5	-3.0	-12.5
15.6	161.6	-124.4	-121.0	-2.0	-13.0
16.8	154.9	-140.5	-132.5	-2.0	-13.0
18.0	145.3	-154.6	-143.5	-3.0	-13.5
19.2	133.1	-167.1	-154.0	-2.0	-13.5
20.4	118.8	-176.2	-165.0	-2.0	-13.5
21.6	102.9	-183.2	-176.0	-3.0	-14.0
22.8	86.5	-187.1	-187.5	-2.0	-14.5
24.0	69.6	-187.8	-197.5	-2.0	-13.0
25.2	52.7	-185.1	-208.0	-2.0	-14.0
26.4	37.1	-179.3	-218.0	-3.0	-14.0
27.6	22.3	-170.5	-230.0	-3.0	-13.5
28.9	9.7	-159.9	-240.5	-3.0	-13.0
30.1	-1.4	-145.3	-251.5	-5.0	-13.0
31.3	-9.0	-129.3	-262.5	-3.0	-13.0
32.5	-13.5	-112.3	-273.0	-3.0	-13.0
33.7	-14.6	-93.8	-284.5	-5.0	-13.0
34.9	-12.0	-74.7	-296.0	-5.0	-13.0
36.1	-4.2	-58.1	-309.0	-5.0	-13.0
37.3	4.0	-41.5	-321.5	-6.0	-13.0
38.5	18.0	-28.1	-334.5	-5.0	-13.0
39.7	33.9	-17.9	-345.0	-4.0	-13.0
40.9	51.5	-11.0	-356.0	-4.0	-13.0
42.1	69.8	-7.4	-368.5	-4.0	-13.0
43.3	88.6	-7.6	-380.5	-3.0	-13.0
44.5	106.6	-11.0	-391.0	-2.0	-13.0
45.7	119.7	-16.4	-399.0	-3.0	-13.0

TABLE 7 Full-scale trajectory measured from overhead photographs.
Approach speed: 10 knots Rudder angle: 30 deg
Rudder rate: 5 deg/sec

Time sec	x ft	y ft	Heading angle deg	Roll angle deg	Drift angle deg
.0	.0	.0	.0	.0	1.0
1.2	22.7	.0	-1.0	-2.0	.0
2.4	44.4	-.5	-4.0	-2.0	-1.5
3.6	66.1	-1.7	-8.5	-3.0	-2.5
4.8	86.9	-4.7	-15.0	-3.0	-5.5
6.0	107.0	-9.0	-22.0	-4.0	-7.0
7.2	126.3	-16.1	-31.5	-5.0	-10.0
8.4	143.5	-24.8	-42.0	-5.0	-10.0
9.6	158.7	-36.5	-53.5	-5.0	-11.0
10.8	171.0	-48.3	-64.0	-3.0	-12.5
12.0	181.0	-63.6	-75.0	-3.0	-11.5
13.2	188.4	-80.2	-86.0	-3.0	-13.0
14.4	192.0	-97.7	-96.5	-3.0	-13.0
15.6	192.5	-114.6	-106.0	-2.0	-13.5
16.8	189.6	-133.9	-118.5	-3.0	-13.0
18.0	182.9	-150.3	-129.5	-2.0	-13.0
19.2	173.3	-165.6	-141.0	-2.0	-13.0
20.4	160.2	-178.6	-151.0	-3.0	-11.0
21.6	145.8	-189.5	-162.0	-3.0	-12.0
22.8	129.5	-197.8	-172.5	-3.0	-13.0
24.0	112.1	-202.2	-182.5	-3.0	-13.0
25.2	94.4	-202.9	-195.0	-3.0	-13.0
26.4	76.9	-201.1	-207.5	-3.0	-13.0
27.6	60.4	-194.7	-220.0	-3.0	-12.0
28.9	44.9	-185.4	-231.0	-2.0	-12.5
30.1	32.1	-173.3	-242.0	-3.0	-12.0
31.3	21.9	-158.9	-252.5	-3.0	-12.5
32.5	14.3	-142.6	-263.0	-3.0	-13.0
33.7	9.4	-125.5	-274.0	-3.0	-13.0
34.9	9.0	-107.6	-285.5	-3.0	-13.0
36.1	11.3	-90.2	-298.0	-3.0	-13.0
37.3	15.9	-75.0	-309.0	-4.0	-13.0
38.5	24.8	-59.4	-320.0	-5.0	-13.0
39.7	37.1	-45.9	-332.0	-4.0	-13.0
40.9	51.6	-35.4	-343.5	-3.0	-13.5
42.1	67.9	-27.9	-355.0	-3.0	-14.0
43.3	84.6	-24.2	-364.0	-4.0	-12.5
44.5	103.2	-23.3	-375.0	-5.0	-12.5
45.7	121.8	-25.9	-386.5	-5.0	-12.0
46.9	138.7	-31.9	-397.5	-3.0	-12.0
48.1	154.7	-41.6	-409.0	-3.0	-12.0
49.3	168.2	-53.9	-418.0	-3.0	-12.0

TABLE 8 Full-scale trajectory measured from overhead photographs.
Approach speed: 27 knots Rudder angle: 20 deg
Rudder rate: 10 deg/sec

Time sec	x ft	y ft	Heading angle deg	Roll angle deg	Drift angle deg
.0	.0	.0	.0	-1.0	.0
.6	27.4	-.3	.0	-1.0	.0
1.2	55.0	-.6	-1.0	.0	.0
1.8	82.2	-1.5	-2.5	-2.0	.0
2.4	109.2	-2.3	-5.5	-7.0	-2.0
3.0	135.9	-4.2	-9.5	-12.0	-3.5
3.6	162.0	-7.3	-14.0	-18.0	-6.0
4.2	187.4	-12.0	-20.0	-23.0	-5.0
4.8	212.5	-19.5	-27.0	-29.0	-7.5
5.4	235.1	-28.5	-34.5	-30.0	-9.0
6.0	256.1	-40.4	-41.5	-27.0	-8.0
6.6	274.7	-54.7	-52.5	-25.0	-11.0
7.2	291.3	-72.0	-61.0	-23.0	-11.0
7.8	304.4	-90.9	-69.0	-19.0	-12.0
8.4	315.5	-110.7	-76.5	-18.0	-11.0
9.0	323.6	-132.5	-83.0	-18.0	-10.0
9.6	329.1	-154.5	-89.0	-20.0	-10.0
10.2	332.0	-177.1	-95.5	-22.0	-10.0
10.8	332.9	-200.4	-101.5	-23.0	-9.5
11.4	330.2	-223.4	-109.0	-23.0	-9.5
12.0	325.1	-245.6	-115.0	-25.0	-9.0
12.6	317.2	-267.6	-121.5	-25.0	-10.0
13.2	306.9	-290.4	-128.5	-27.0	-11.0
13.8	293.9	-313.9	-136.5	-28.0	-11.5
14.4	277.3	-332.8	-144.0	-27.0	-11.5
15.0	261.3	-348.6	-152.0	-27.0	-11.5
15.6	242.2	-361.9	-161.0	-25.0	-12.0
16.2	220.0	-373.3	-170.0	-23.0	-12.0
16.8	196.8	-383.1	-175.5	-25.0	-11.5
17.4	173.6	-387.5	-183.0	-25.0	-12.0
18.0	150.0	-388.4	-190.5	-26.0	-11.5
18.6	126.8	-387.5	-197.5	-26.0	-11.5

TABLE 9 Full-scale trajectory measured from overhead photographs.
Approach speed: 27 knots Rudder angle: 20 deg
Rudder rate: 5 deg/sec

Time sec	x ft	y ft	Heading angle deg	Roll angle deg	Drift angle deg
.0	.0	.0	.0	1.0	.0
.6	27.5	.0	.0	.0	.0
1.2	55.1	-.3	-1.5	-1.0	-1.0
1.8	82.5	-.8	-3.0	-3.0	-1.0
2.4	109.9	-2.4	-5.0	-6.0	-2.0
3.0	137.1	-3.6	-7.0	-7.0	-3.0
3.6	163.7	-6.4	-10.0	-10.0	-4.0
4.2	190.1	-9.4	-14.0	-12.0	-5.0
4.8	216.0	-14.4	-18.5	-15.0	-6.5
5.4	241.2	-20.5	-22.5	-17.0	-6.0
6.0	265.8	-30.0	-27.0	-21.0	-7.0
6.6	289.7	-39.2	-32.5	-24.0	-9.0
7.2	312.4	-50.8	-39.5	-27.0	-10.0
7.8	333.3	-64.8	-47.0	-28.0	-10.0
8.4	351.6	-80.9	-54.0	-29.0	-9.0
9.0	367.6	-99.1	-61.0	-28.0	-9.5
9.6	380.9	-118.5	-68.5	-27.0	-9.0
10.2	391.2	-139.0	-72.0	-24.0	-9.5
10.8	398.9	-160.1	-83.5	-23.0	-9.5
11.4	404.8	-182.7	-90.0	-20.0	-9.5
12.0	405.9	-206.5	-97.0	-18.0	-9.5
12.6	405.0	-230.1	-103.5	-18.0	-10.0
13.2	403.1	-254.5	-110.0	-19.0	-10.5
13.8	397.7	-278.3	-115.5	-21.0	-8.0
14.4	387.5	-300.7	-122.0	-24.0	-8.5
15.0	376.2	-322.3	-128.5	-26.0	-9.5
15.6	363.6	-342.7	-135.5	-27.0	-10.0
16.2	348.5	-360.6	-142.0	-27.0	-10.0
16.8	332.4	-376.9	-150.5	-27.0	-10.0
17.4	312.6	-390.8	-157.5	-27.0	-10.0
18.0	292.2	-401.8	-165.5	-24.0	-10.0
18.6	270.9	-409.8	-174.0	-23.0	-10.0
19.2	248.9	-414.8	-180.5	-20.0	-10.0
19.8	226.2	-416.1	-187.5	-19.0	-10.0
20.4	202.8	-417.2	-193.5	-20.0	-10.0
21.0	180.8	-414.1	-199.5	-18.0	-9.0

TABLE 10 Full-scale trajectory measured from overhead photographs.
Approach speed: 27 knots Rudder angle: 30 deg
Rudder rate: 10 deg/sec

Time sec	x ft	y ft	Heading angle deg	Roll angle deg	Drift angle deg
.0	.0	.0	.0	-1.0	.0
.6	27.4	.0	.0	-1.0	-.5
1.2	54.5	.8	.0	-3.0	-.5
1.8	81.0	-.2	-2.5	-6.0	-.5
2.4	106.7	-.8	-5.5	-9.0	-1.5
3.0	131.6	-2.5	-8.5	-14.0	-3.0
3.6	155.3	-4.8	-14.0	-19.0	-6.0
4.2	178.0	-8.7	-20.5	-24.0	-8.5
4.8	199.4	-14.2	-28.5	-28.0	-11.0
5.4	219.4	-21.5	-38.5	-33.0	-13.5
6.0	237.8	-30.2	-46.5	-30.0	-13.0
6.6	254.2	-42.2	-54.0	-24.0	-11.0
7.2	268.0	-60.2	-59.0	-20.0	-8.0
7.8	280.7	-78.2	-64.5	-19.0	-8.0
8.4	292.0	-96.1	-69.0	-19.0	-9.0
9.0	301.8	-115.0	-75.0	-20.0	-9.0
9.6	309.6	-133.9	-84.0	-22.0	-9.0
10.2	314.2	-156.7	-87.5	-25.0	-8.0
10.8	316.5	-177.0	-91.0	-27.0	-7.0
11.4	317.7	-199.1	-95.0	-26.0	-7.0
12.0	317.0	-220.6	-100.0	-26.0	-6.5
12.6	314.1	-242.1	-108.5	-25.0	-8.0
13.2	308.5	-263.8	-117.5	-24.0	-9.0
13.8	299.9	-284.1	-122.0	-23.0	-7.5
14.4	289.2	-303.5	-128.5	-21.0	-8.0
15.0	277.5	-322.6	-133.0	-20.0	-7.0
15.6	264.0	-339.2	-138.0	-19.0	-8.0
16.2	249.4	-355.1	-144.5	-20.0	-7.0

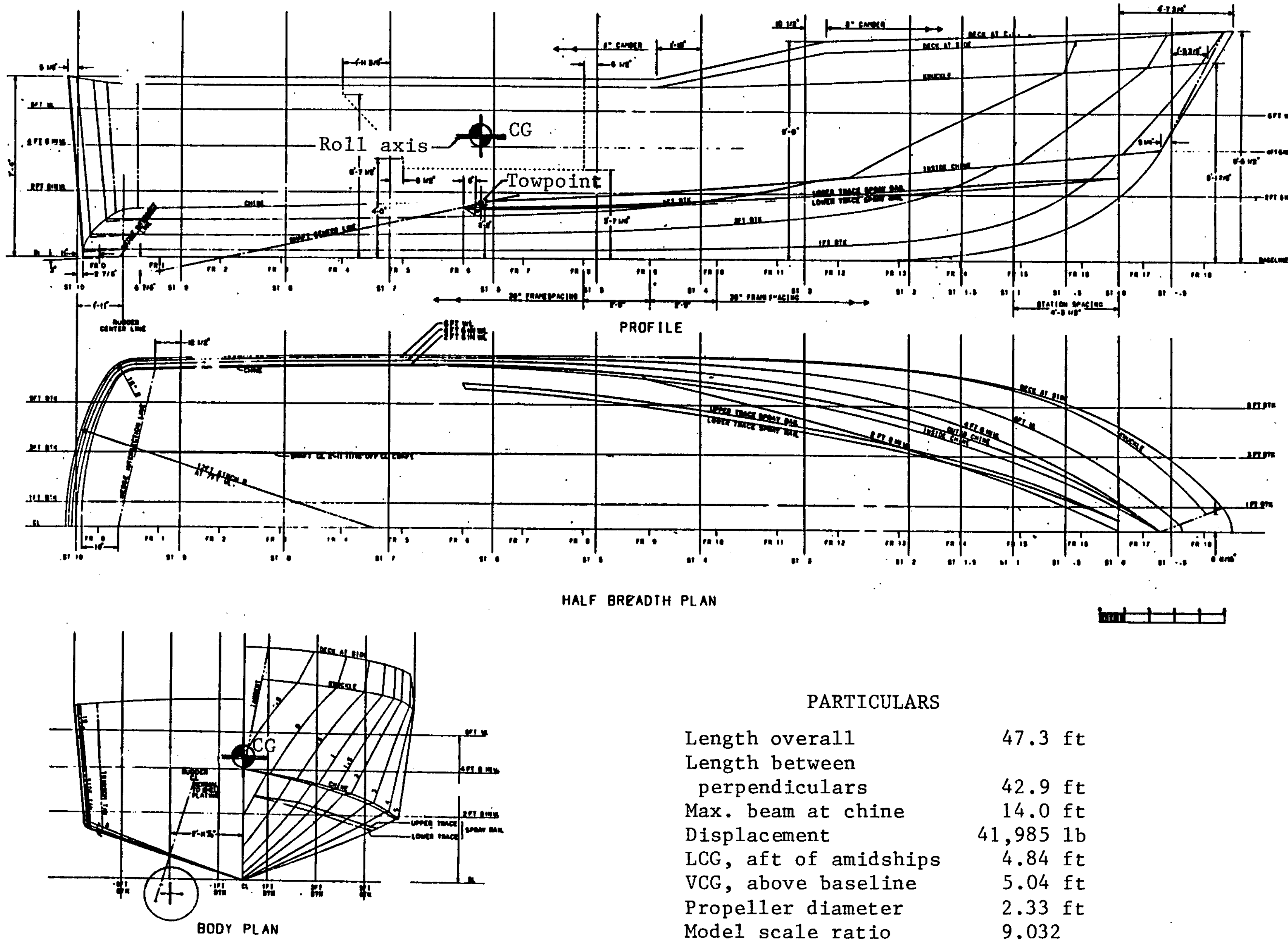
TABLE 11 Full-scale trajectory measured from overhead photographs.
Approach speed: 27 knots Rudder angle: 30 deg
Rudder rate: 5 deg/sec

Time sec	x ft	y ft	Heading angle deg	Roll angle deg	Drift angle deg
.0	.0	.0	1.0	-1.0	.0
.6	27.4	.0	.0	-1.0	.5
1.2	54.8	-.3	-1.5	-3.0	.5
1.8	82.0	-.9	-2.5	-5.0	.0
2.4	108.9	-2.1	-5.0	-7.0	-1.0
3.0	135.6	-4.0	-8.0	-9.0	-2.5
3.6	161.7	-6.9	-11.0	-10.0	-3.5
4.2	187.4	-11.4	-14.5	-14.0	-4.0
4.8	212.2	-16.7	-19.0	-16.0	-5.0
5.4	236.4	-23.3	-24.5	-18.0	-6.5
6.0	259.0	-32.5	-31.0	-21.0	-7.5
6.6	281.4	-43.6	-38.5	-25.0	-10.0
7.2	302.2	-56.6	-46.5	-30.0	-11.5
7.8	320.7	-71.6	-51.0	-28.0	-8.5
8.4	337.3	-89.1	-54.5	-27.0	-6.0
9.0	351.8	-107.3	-59.5	-28.0	-4.5
9.6	364.7	-126.8	-62.5	-28.0	-5.0
10.2	375.9	-146.2	-67.0	-27.0	-5.0
10.8	385.9	-166.6	-72.0	-26.0	-5.0
11.4	394.4	-188.6	-76.5	-24.0	-6.0
12.0	401.0	-210.4	-81.5	-23.0	-5.5
12.6	405.0	-232.8	-85.5	-24.0	-5.0
13.2	407.9	-255.1	-90.0	-24.0	-5.0
13.8	409.0	-277.4	-95.0	-25.0	-5.0
14.4	408.6	-299.6	-99.0	-24.0	-6.0
15.0	406.3	-321.4	-104.5	-24.0	-6.0

TABLE 12 Full-Scale Turning Parameters

Approach speed, kt	Rudder angle deg	Rudder rate deg/sec	Advance ft	Transfer ft	Tactical diameter ft
10	20	5	214	221	279
10	20	10	185	122	278
10	30	5	190	87	201
10	30	10	164	74	185
27	20	5	405	183	414
27	20	10	330	158	386
27	30	5	408	255	501*
27	30	10	316	171	408*

*Estimated



PARTICULARS

Length overall	47.3 ft
Length between perpendiculars	42.9 ft
Max. beam at chine	14.0 ft
Displacement	41,985 lb
LCG, aft of amidships	4.84 ft
VCG, above baseline	5.04 ft
Propeller diameter	2.33 ft
Model scale ratio	9.032

FIGURE 1 Lines and particulars of the USCG 47 ft Motor Life Boat

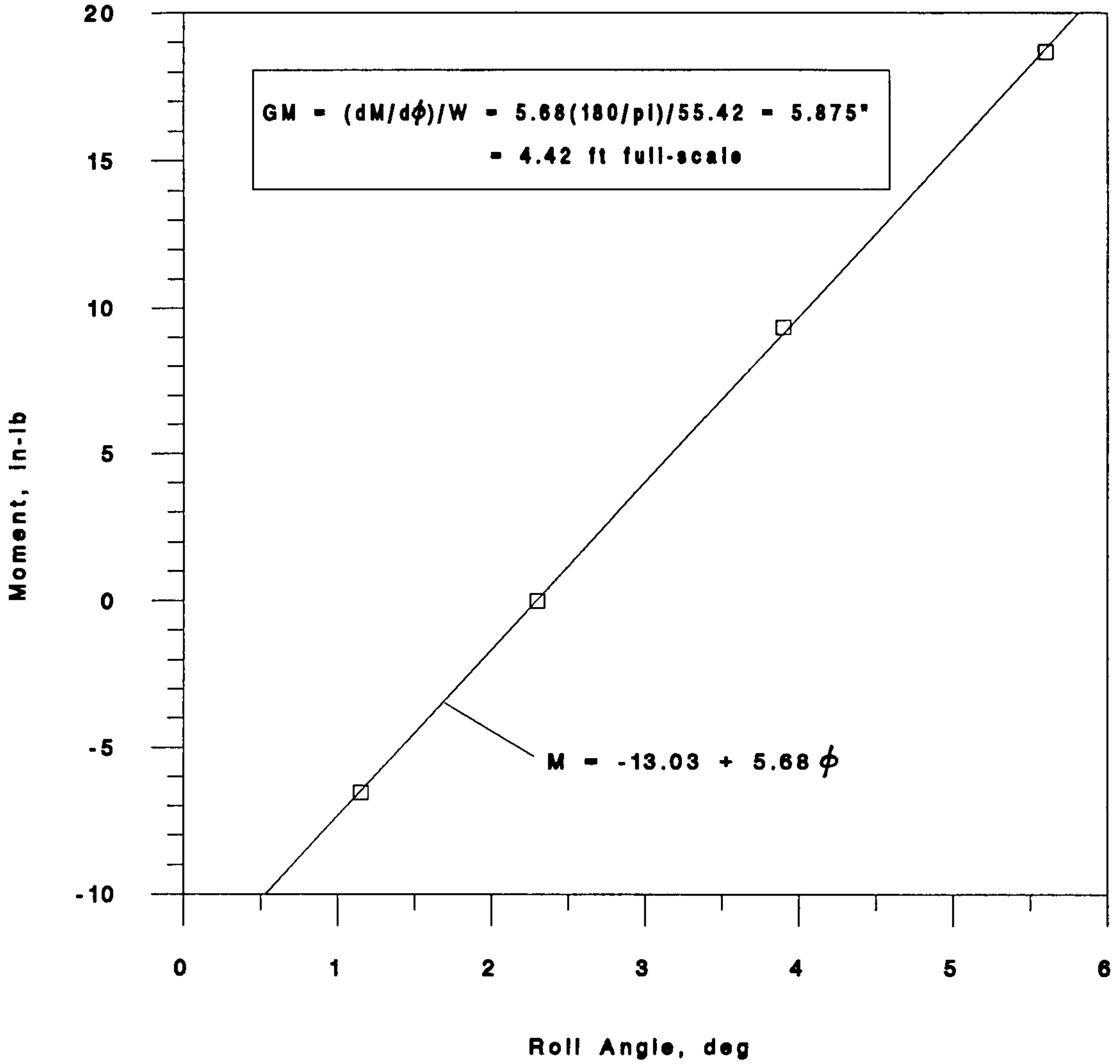


Figure 2 Inclining Experiment

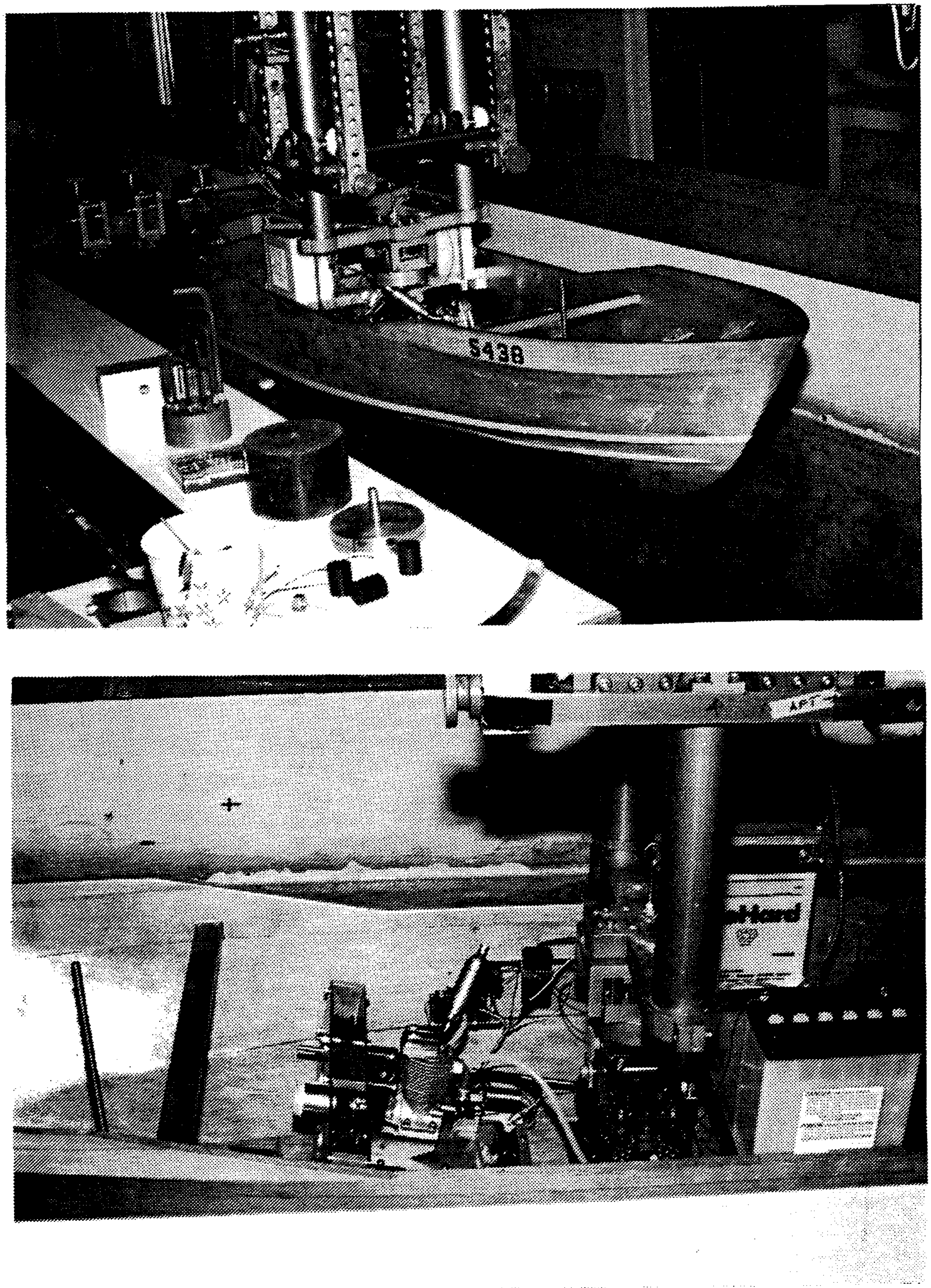


FIGURE 3 Rudder Effectiveness Test Rig

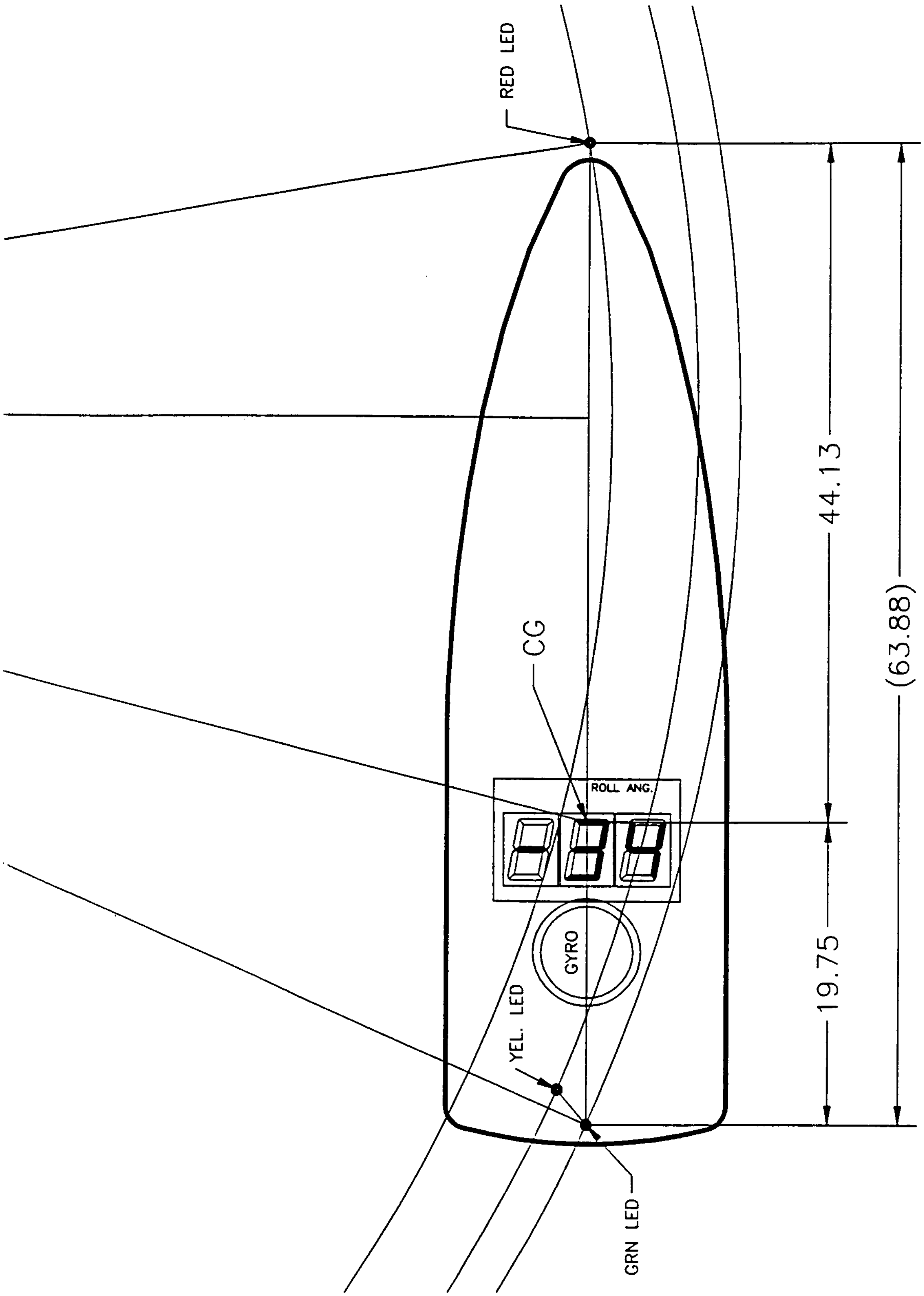


FIGURE 4 INSTRUMENTATION FOR FREE-RUNNING MODEL TESTS. LIGHT LOCATIONS IN INCHES (MODEL)

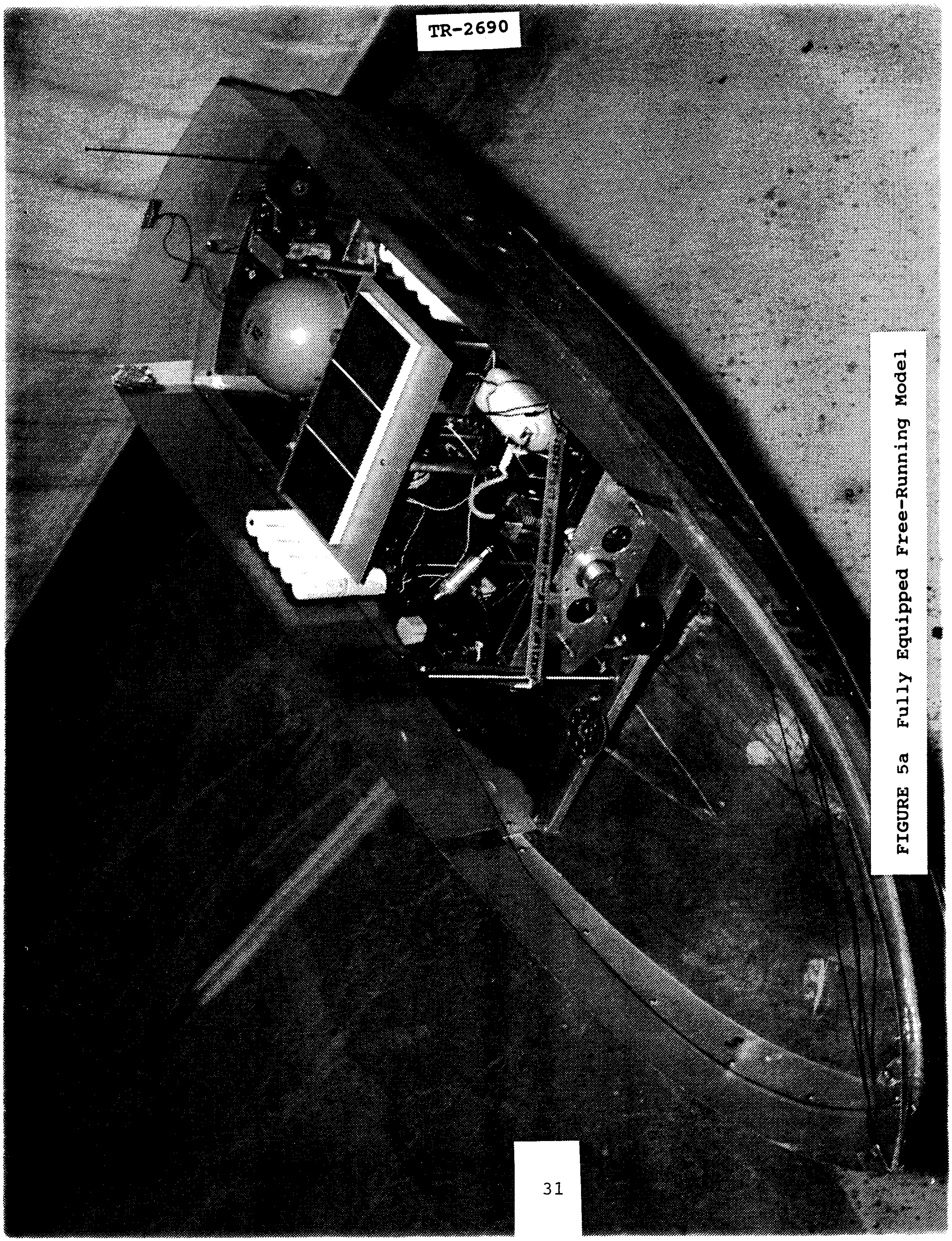


FIGURE 5a Fully Equipped Free-Running Model

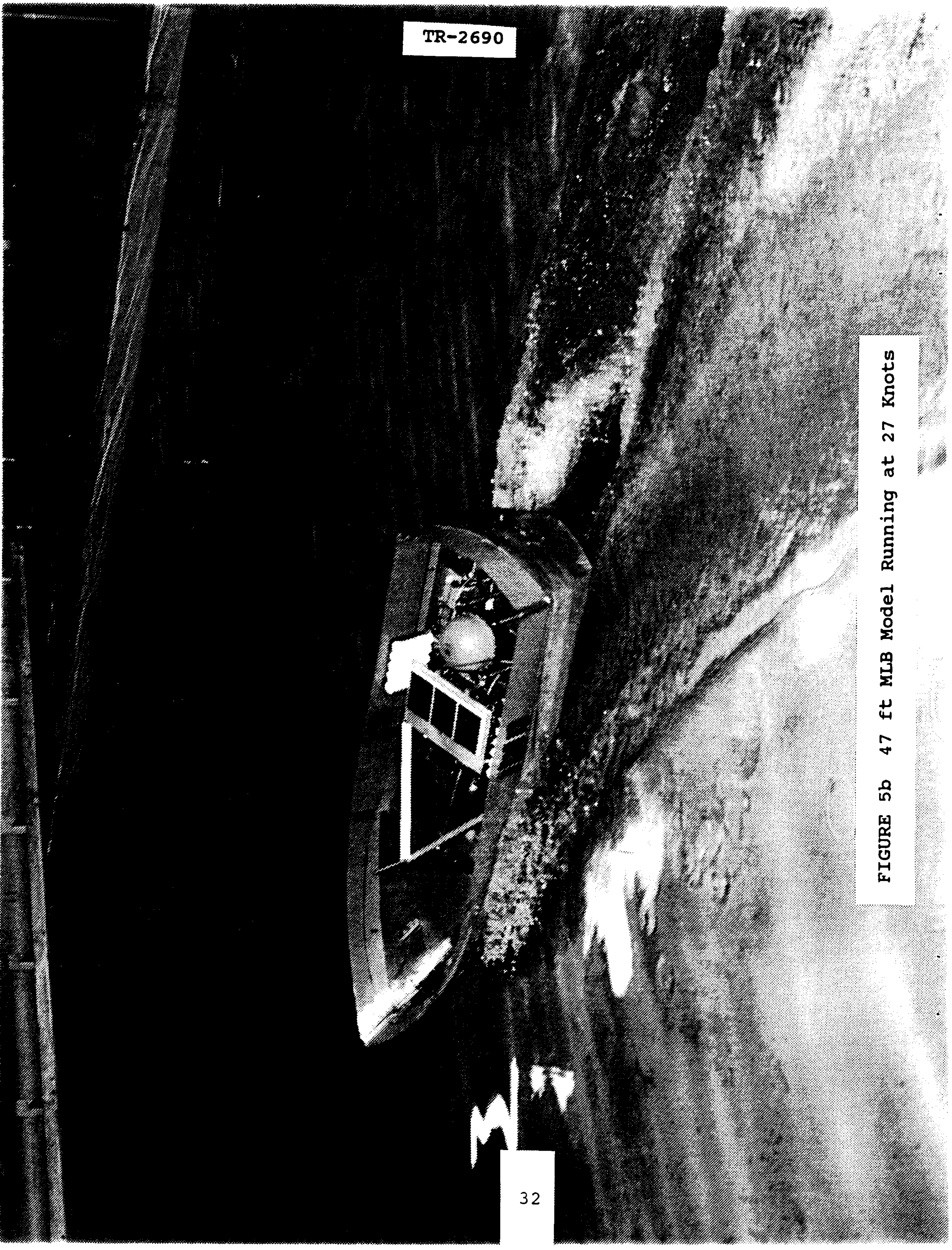


FIGURE 5b 47 ft MLB Model Running at 27 Knots

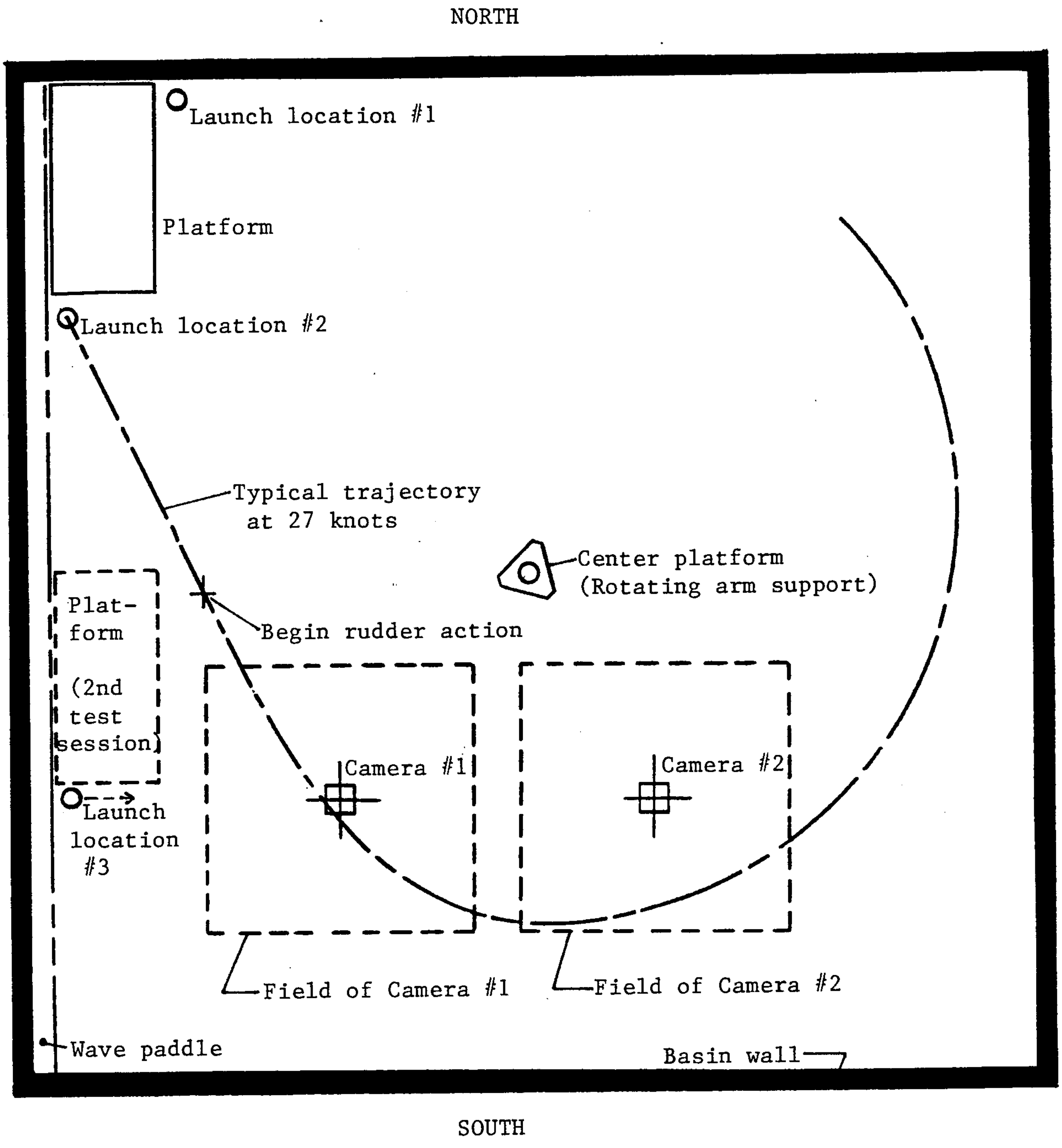


FIGURE 6 Plan View of Maneuvering Basin showing Platform and Camera Locations and a Typical High-Speed Trajectory

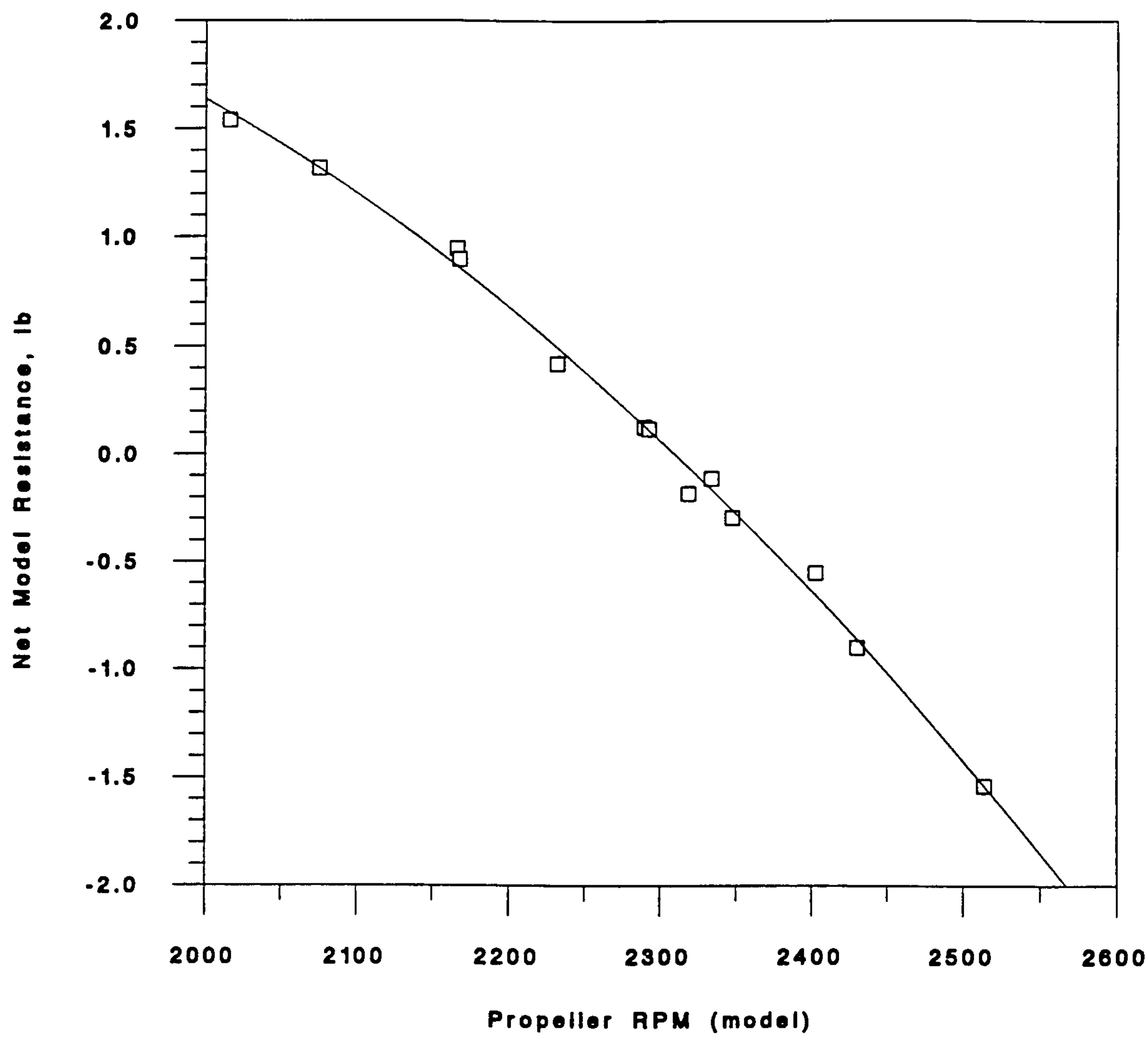


Figure 7 Net Resistance vs Propeller Speed
Speed: 10 knots

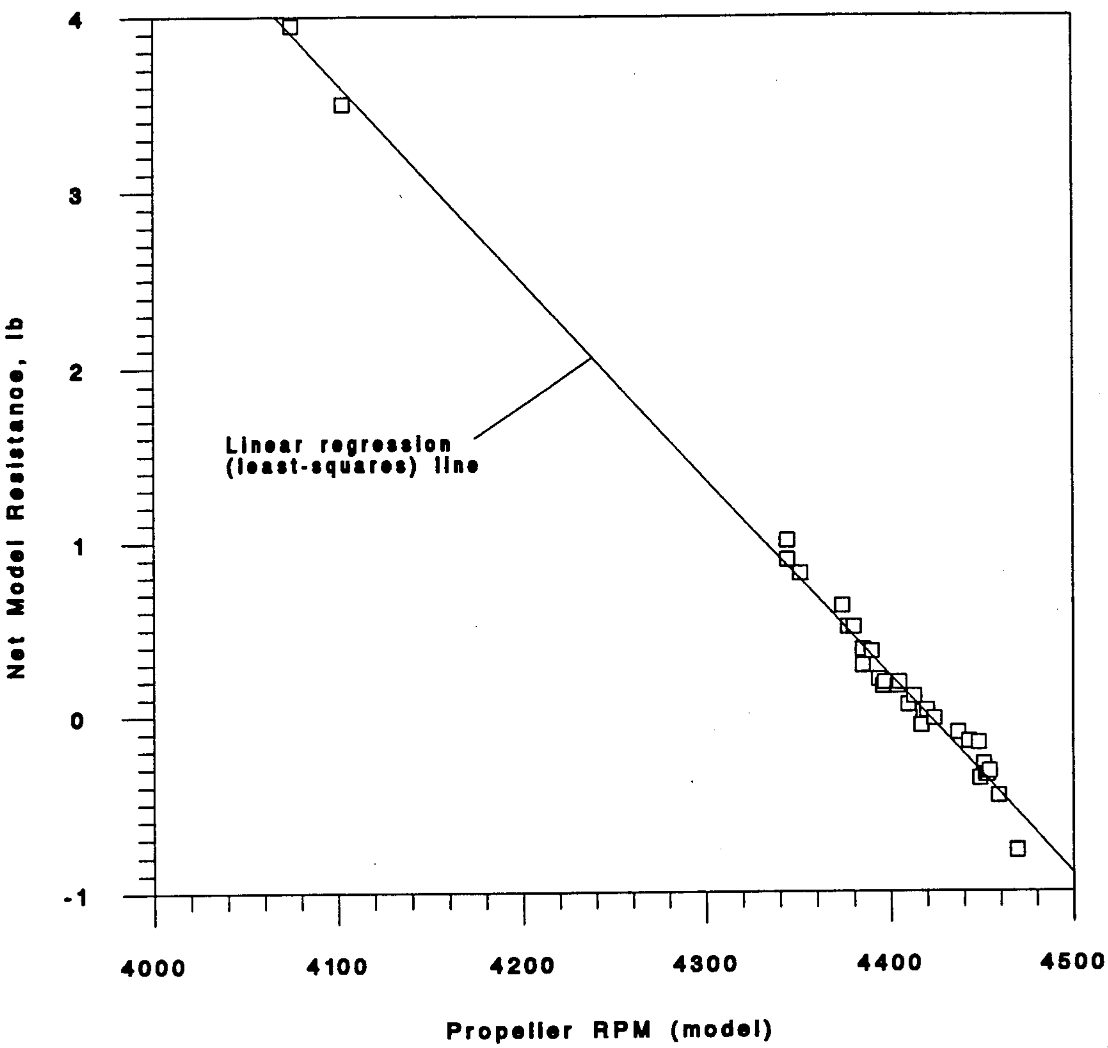


Figure 8 Net Resistance vs Propeller Speed
Speed: 27 knots

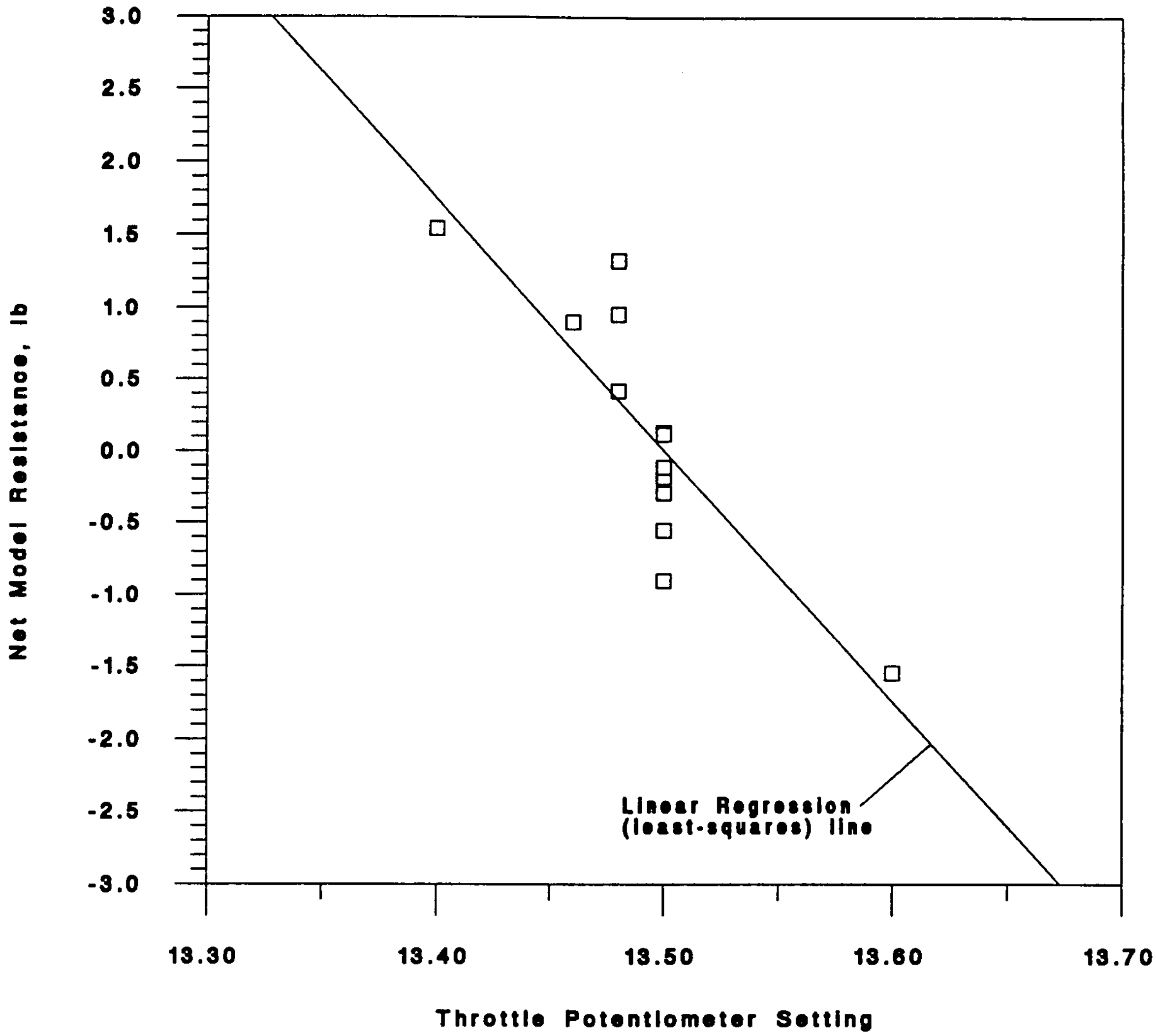


Figure 9 Net Resistance vs Throttle Setting
Speed: 10 knots

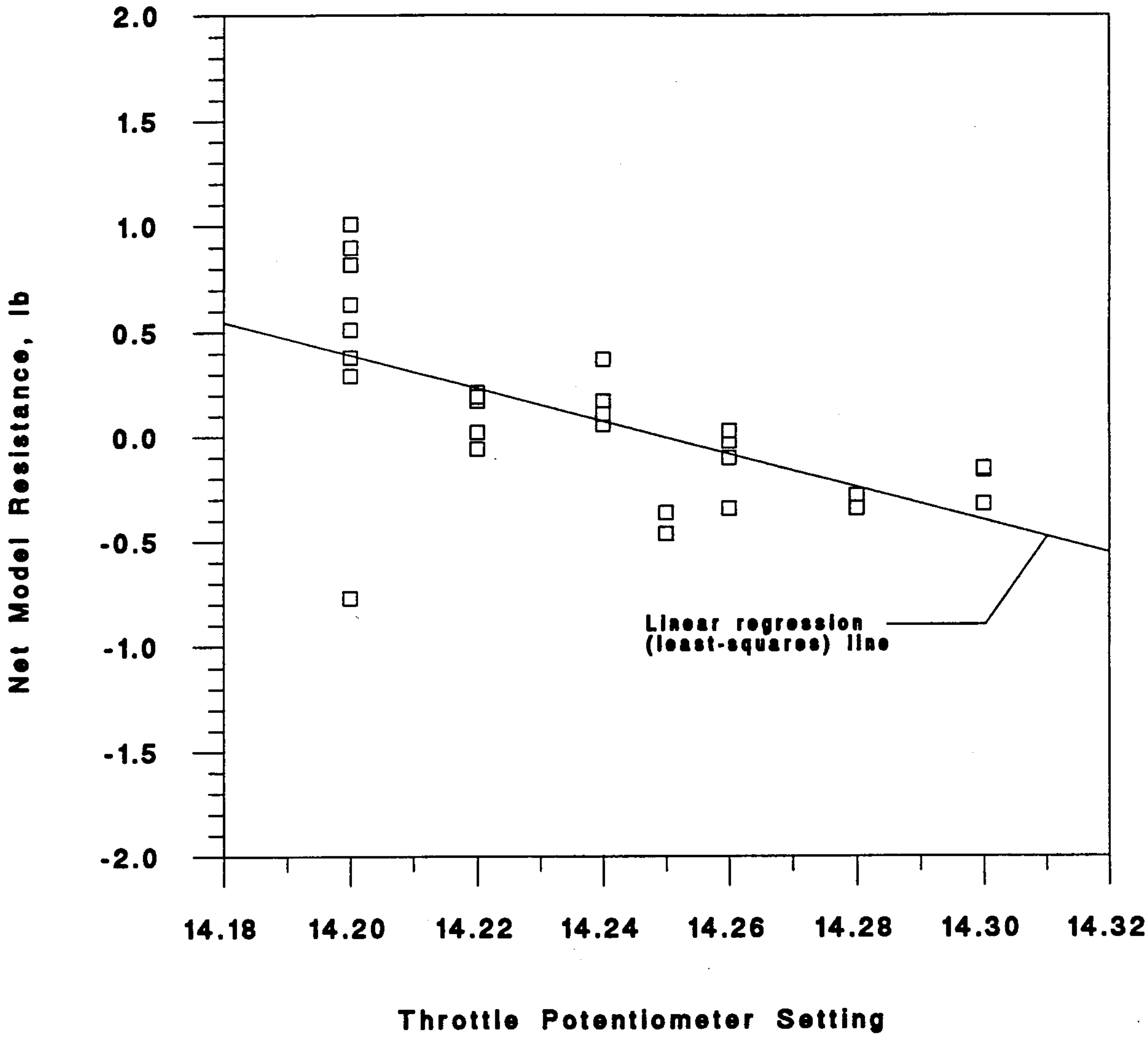


Figure 10 Net Resistance vs Throttle Setting
Speed: 27 knots

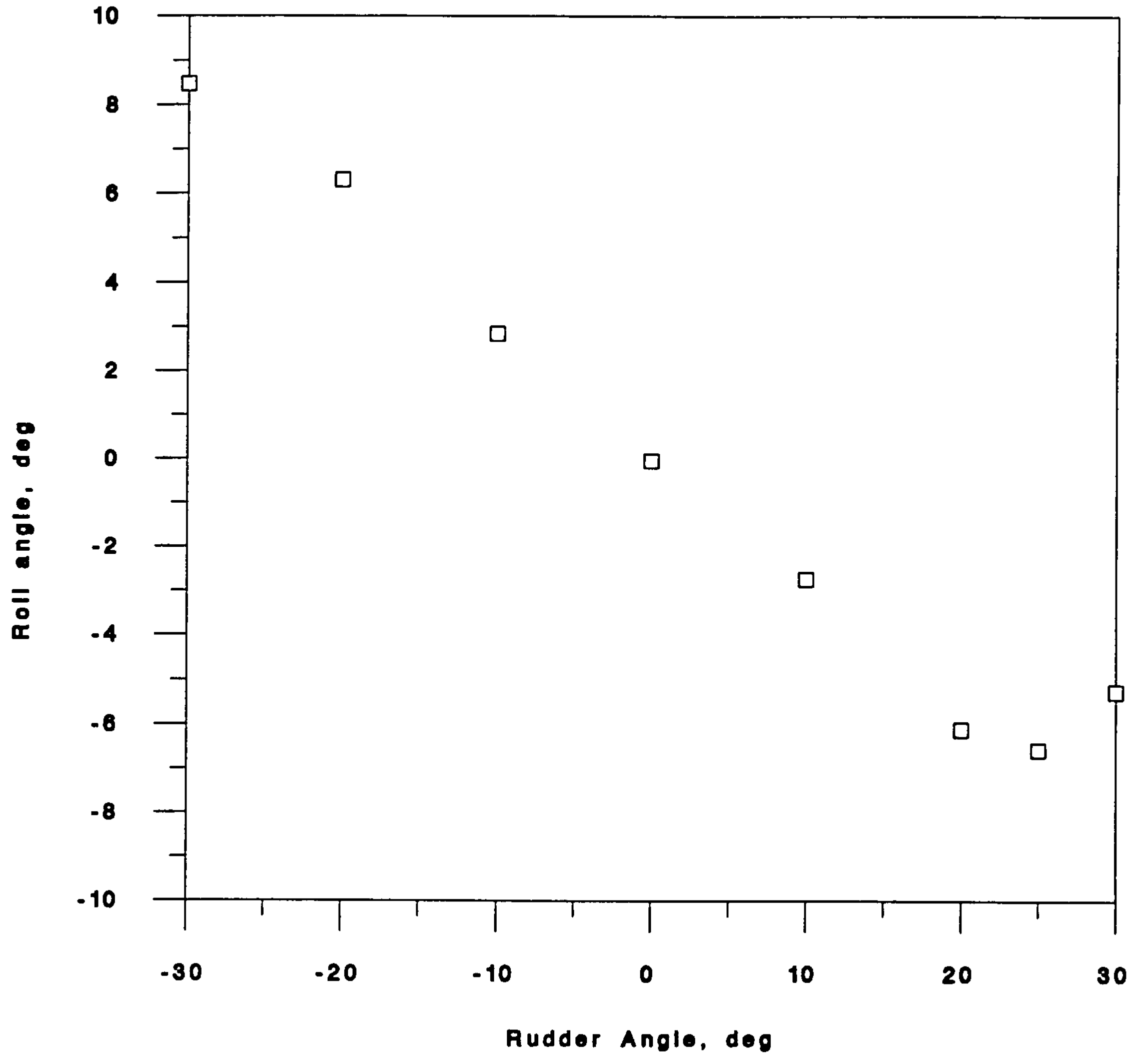


Figure 11 Roll angle vs Rudder Deflection on Straight-Course; Speed = 10 knots

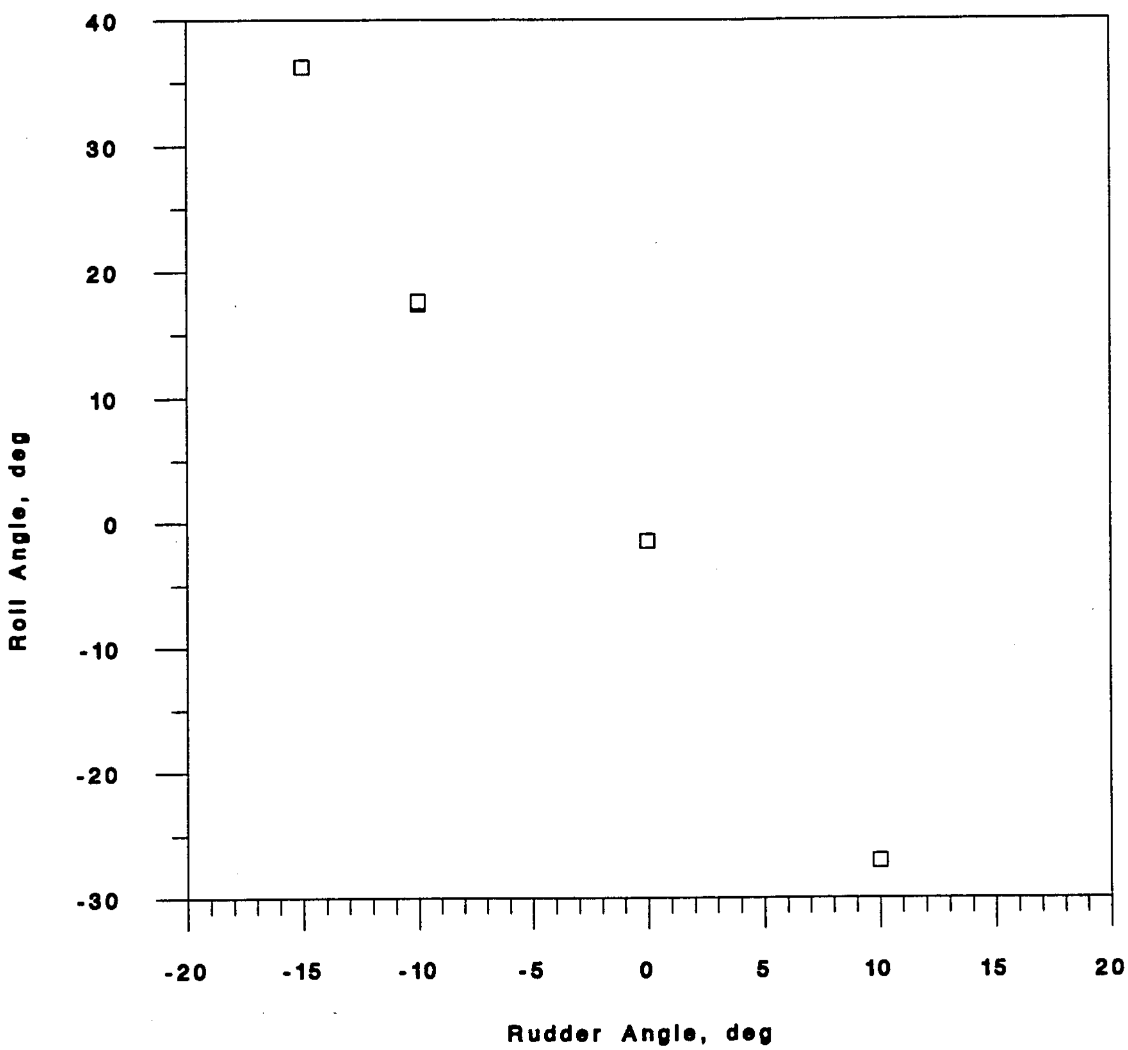


Figure 12 Roll Angle vs Rudder Deflection on Straight Course; Speed = 27 knots

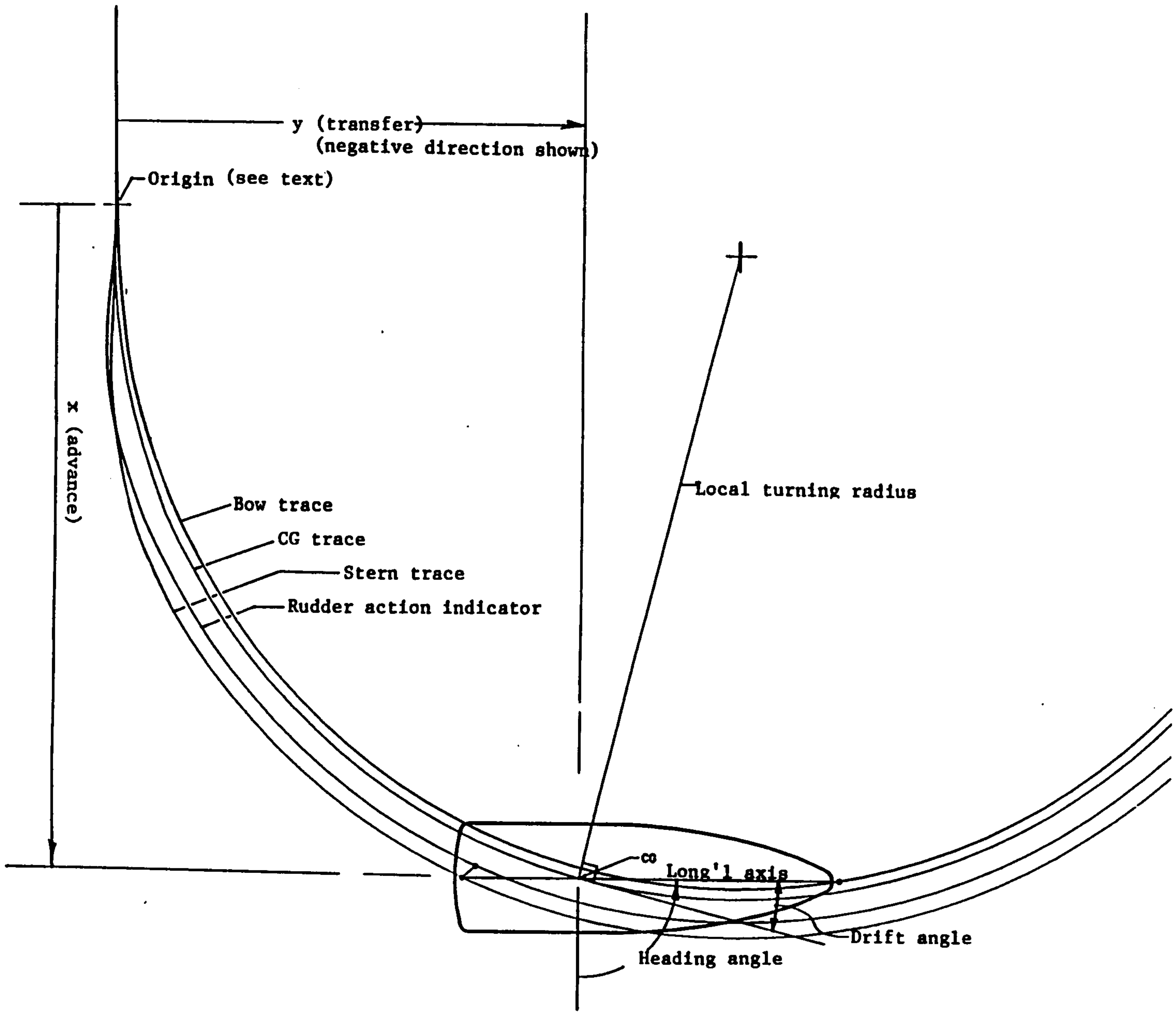
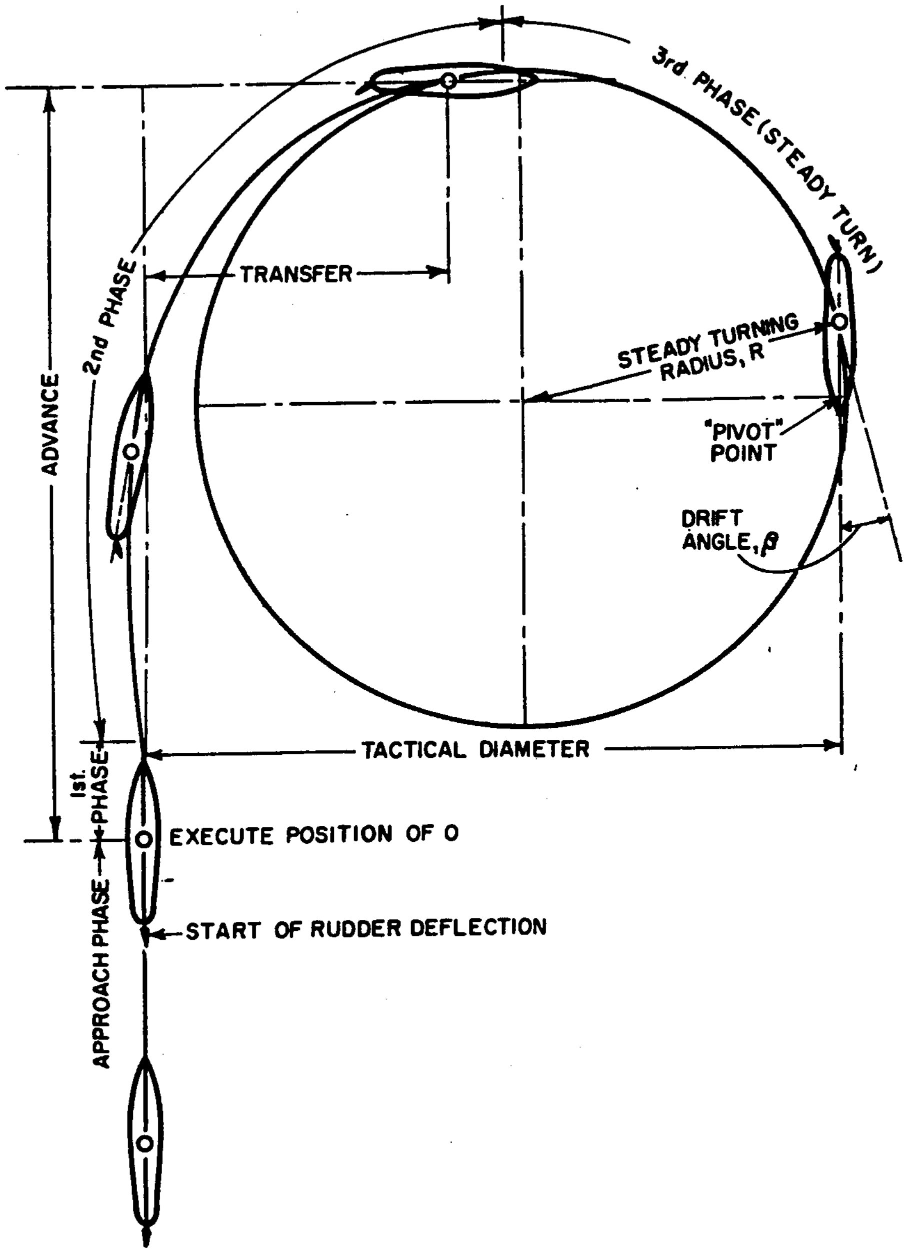


FIGURE 13 Definition of turning parameters and coordinate system



Turning path of a ship

FIGURE 14 Definition of Turning Parameters (from Ref. 1)

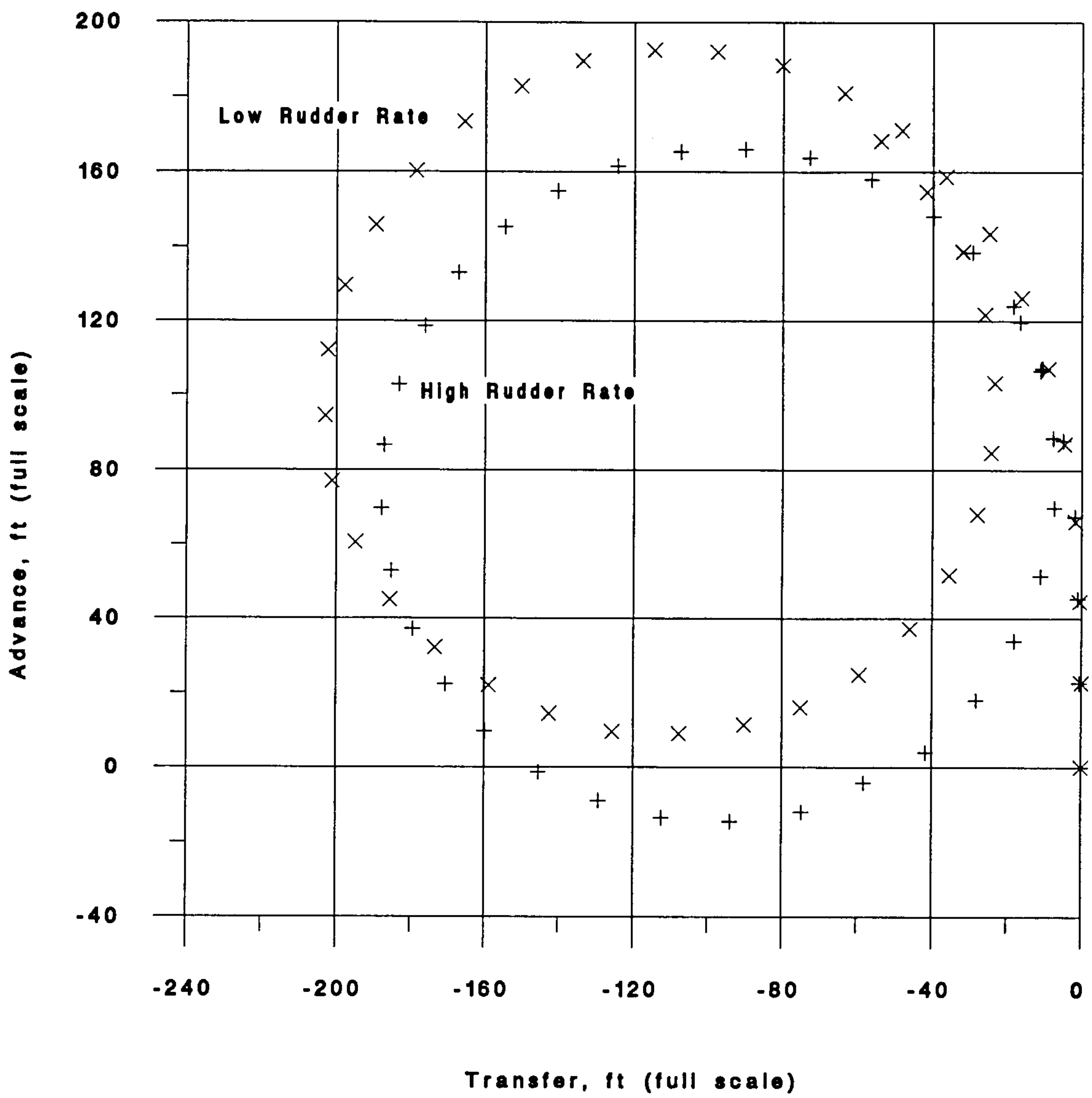


FIGURE 15 Turning Trajectory of 47 ft MLB
Approach: 10 kt Rudder: 30 deg

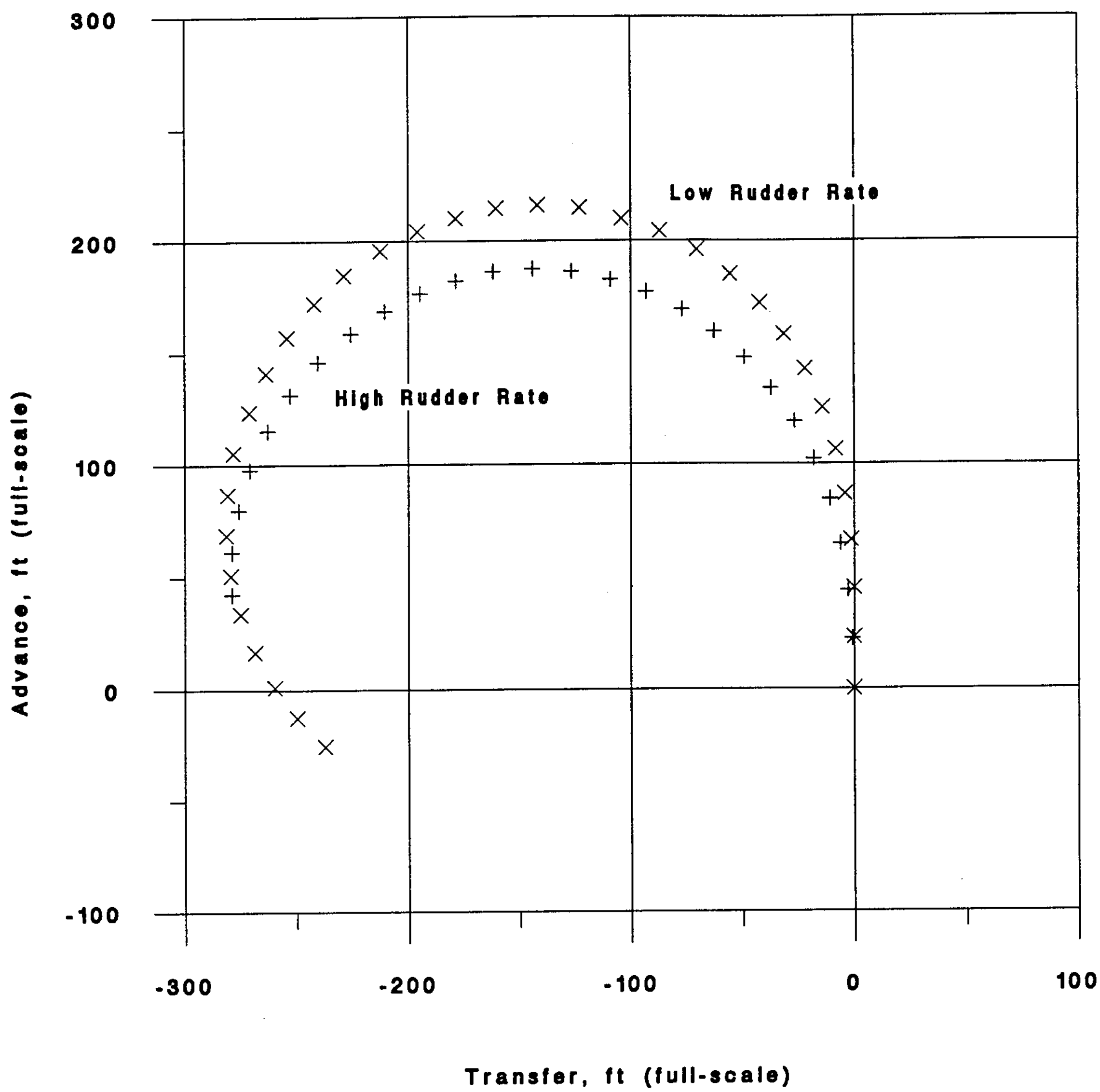


FIGURE 16 Turning Trajectory of 47 ft MLB
Approach: 10 kt Rudder: 20 deg

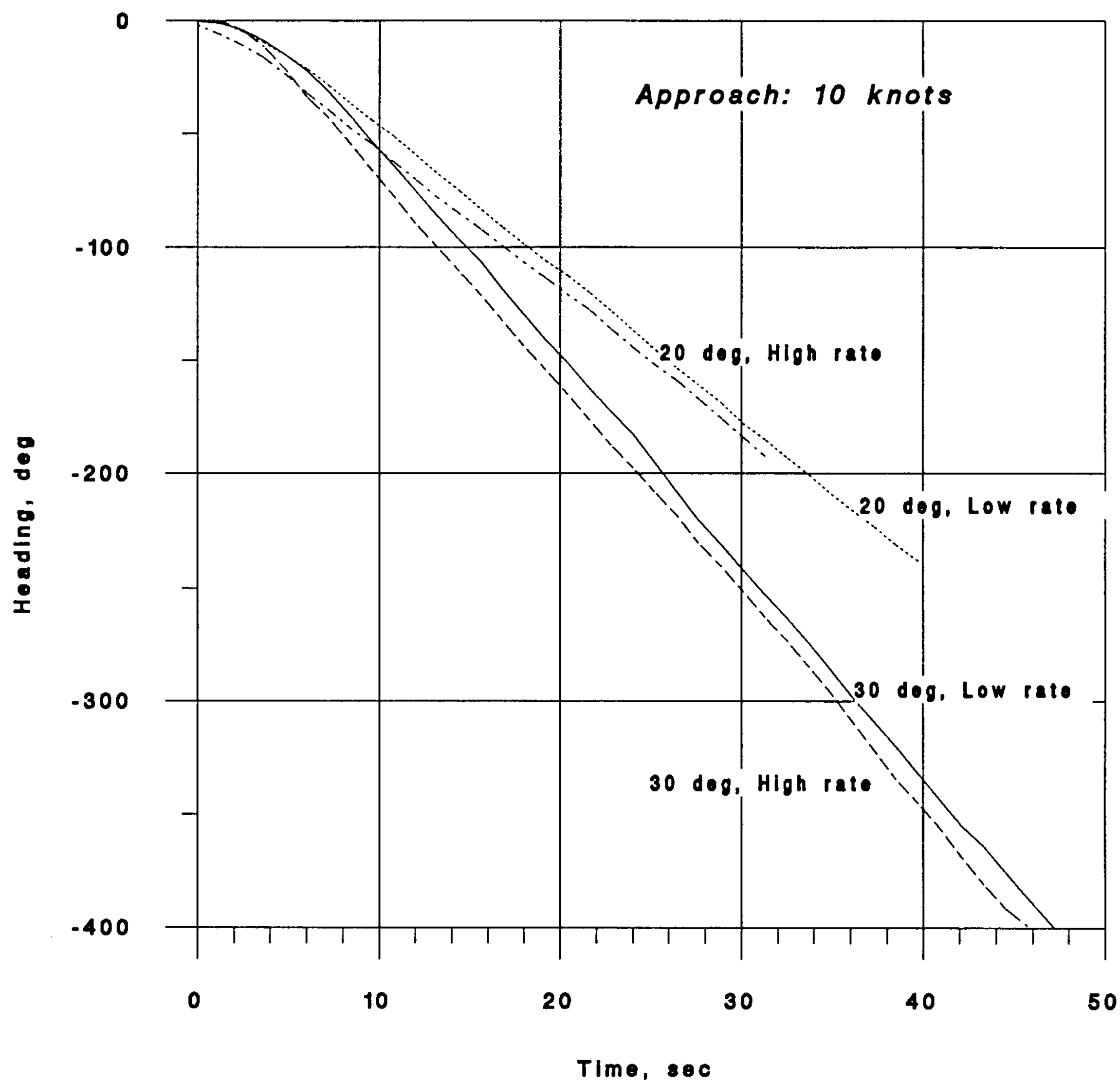


FIGURE 17 Time history of heading in low speed turns. Full scale units.

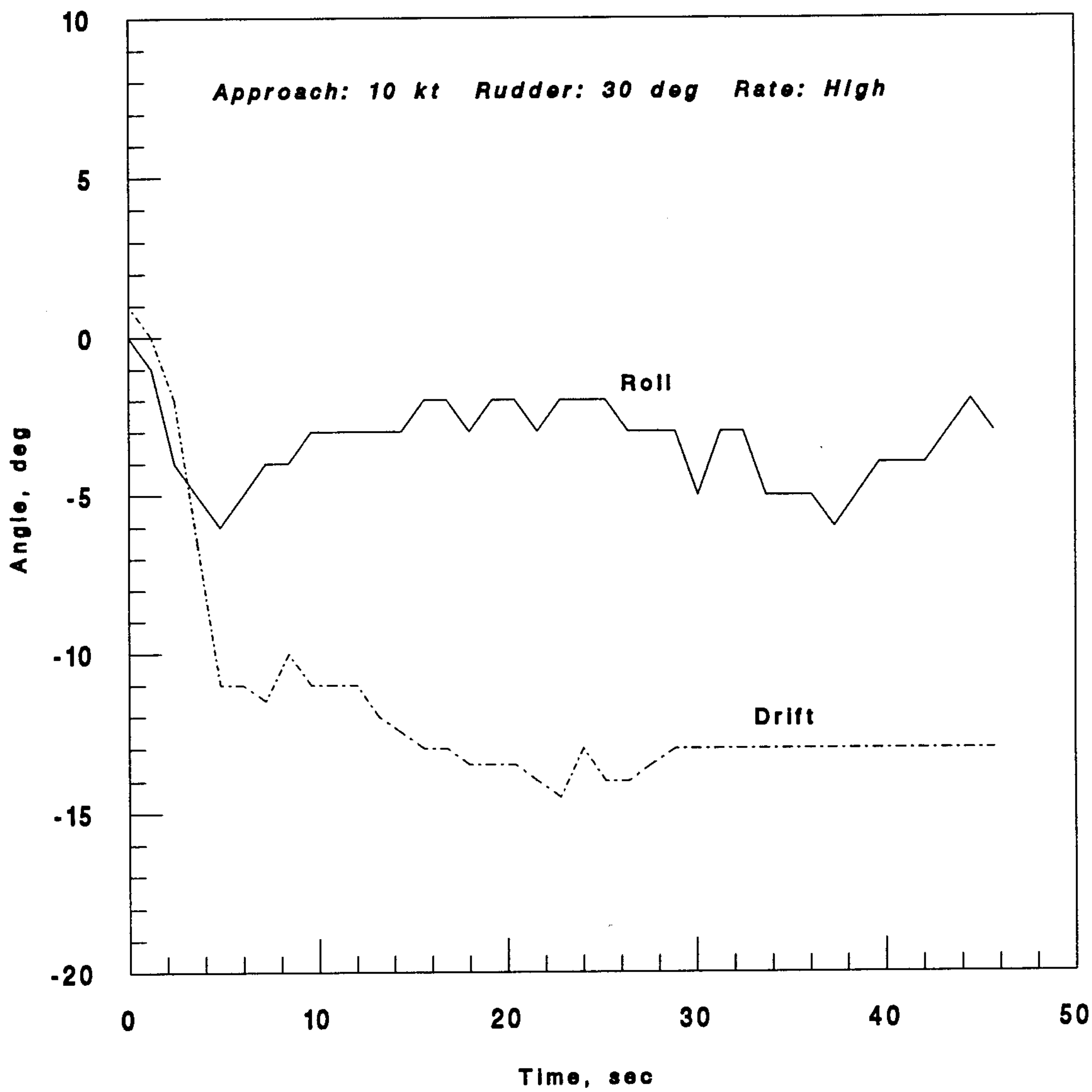


FIGURE 18 Time history of roll and drift angles in a turn. Full scale units.

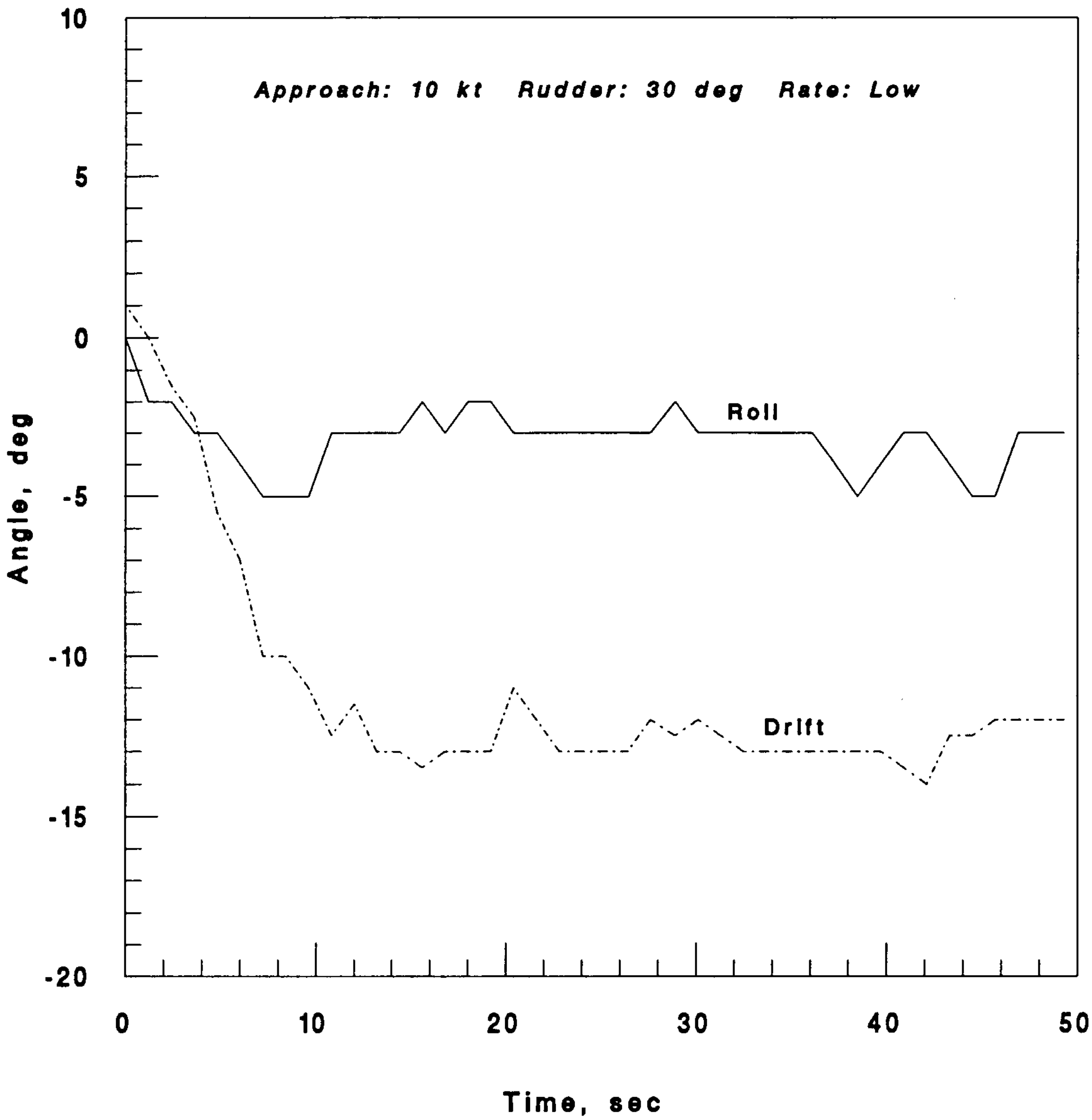


FIGURE 19 Time history of roll and drift angles in a turn. Full scale units.

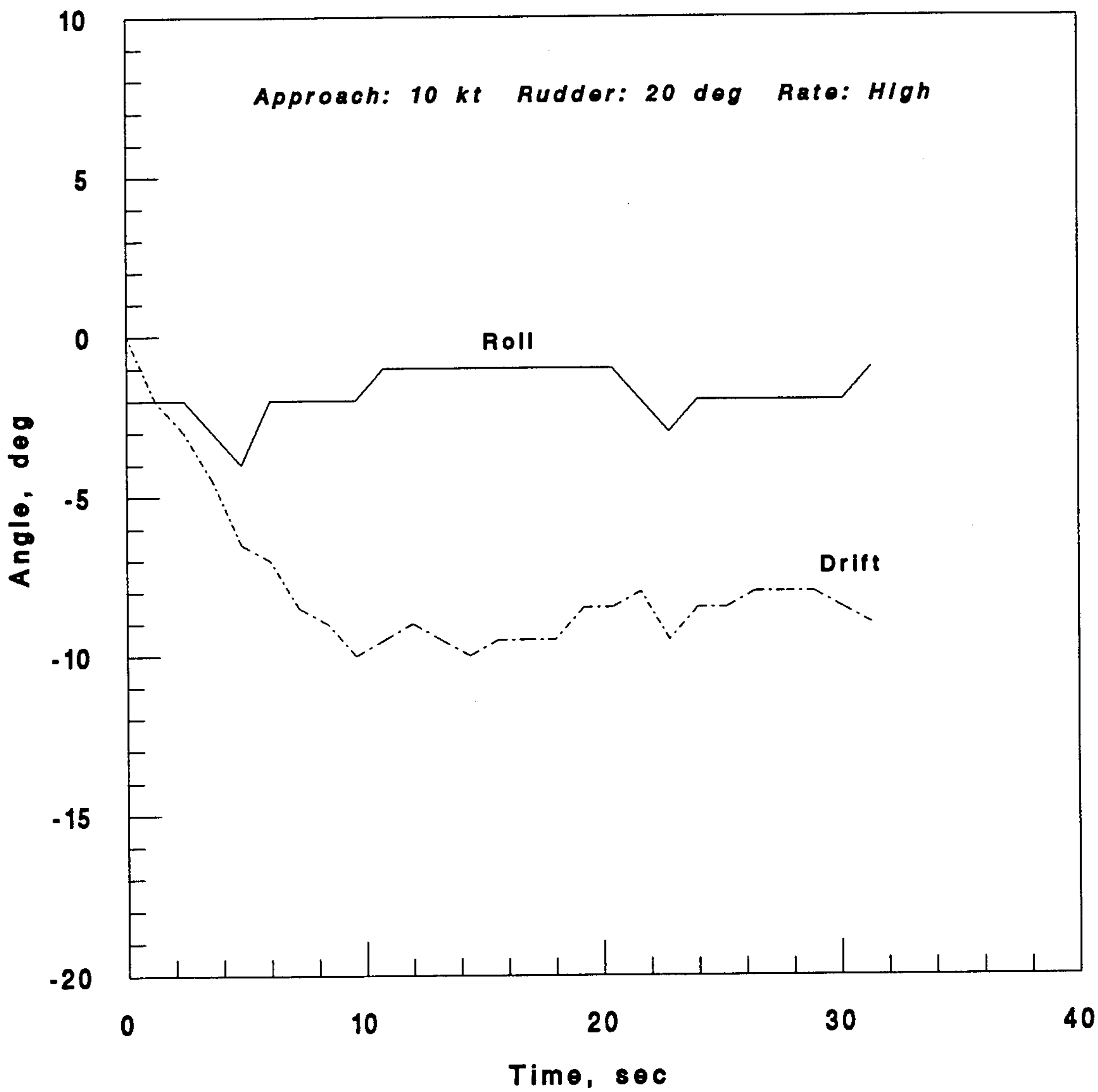


FIGURE 20 Time history of roll and drift angles in a turn. Full scale units.

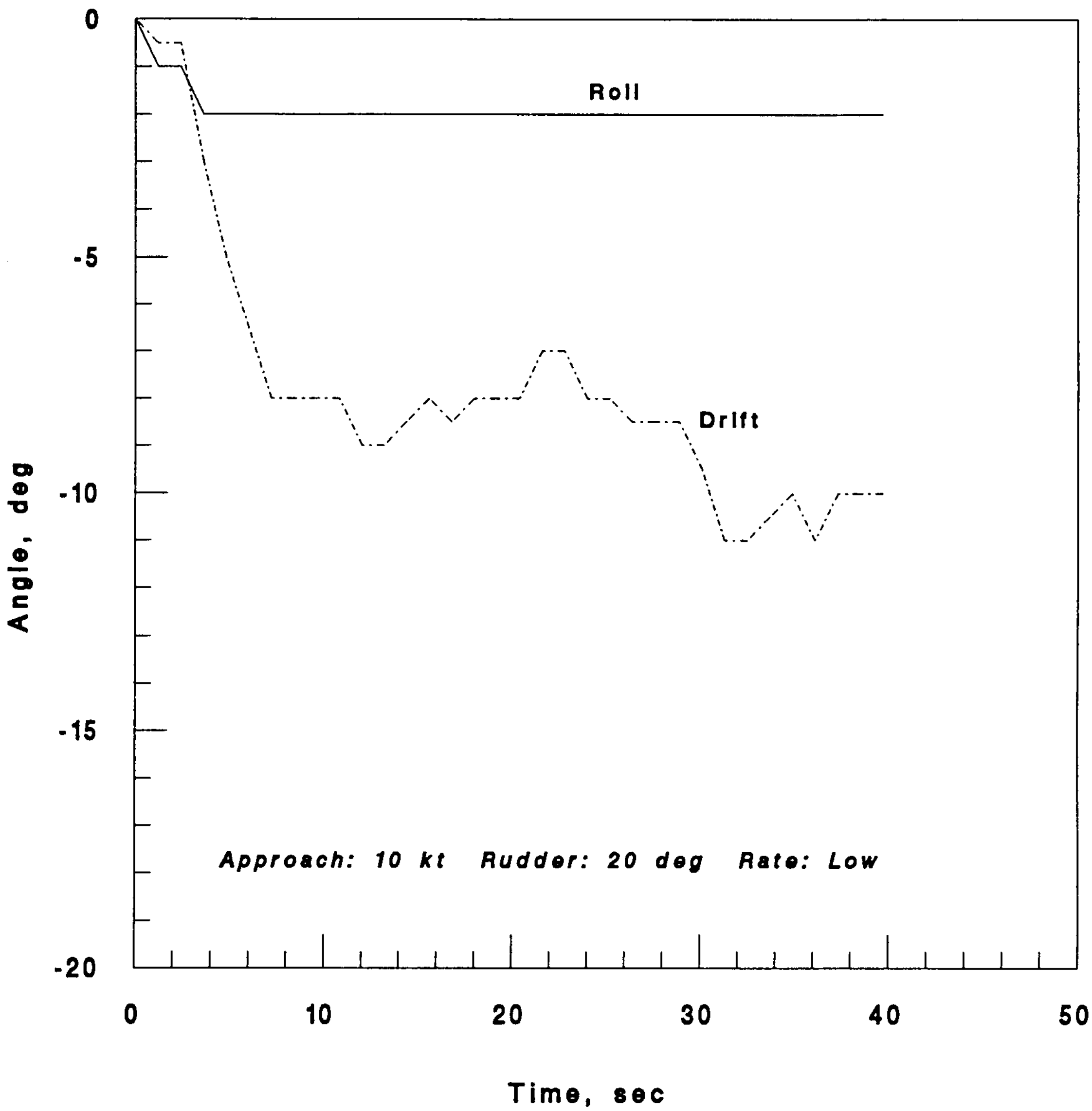


FIGURE 21 Time history of roll and drift angles in a steady turn. Full scale units.

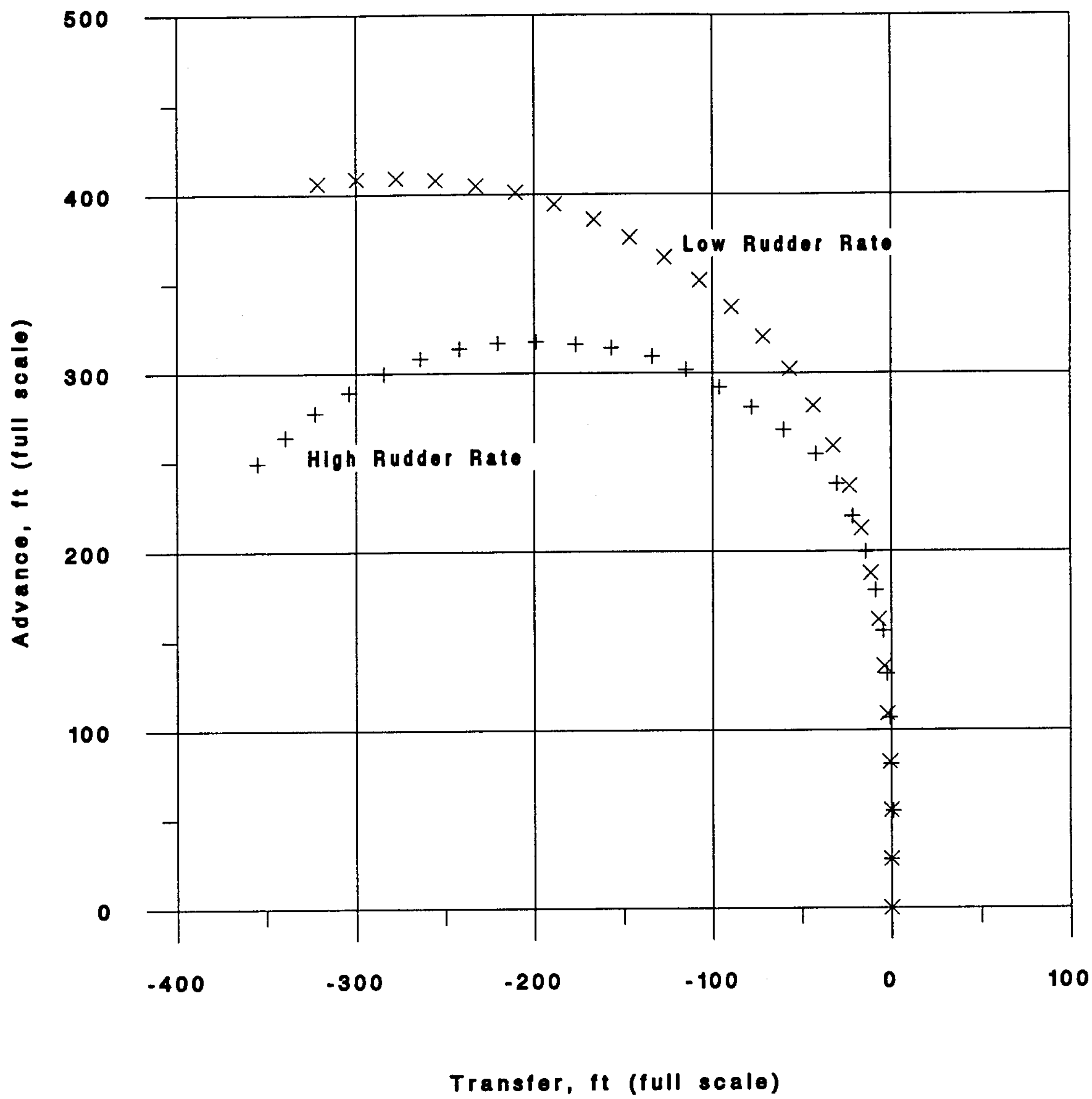


FIGURE 22 Turning Trajectory of 47 ft MLB
Approach:27 kt Rudder: 30 deg

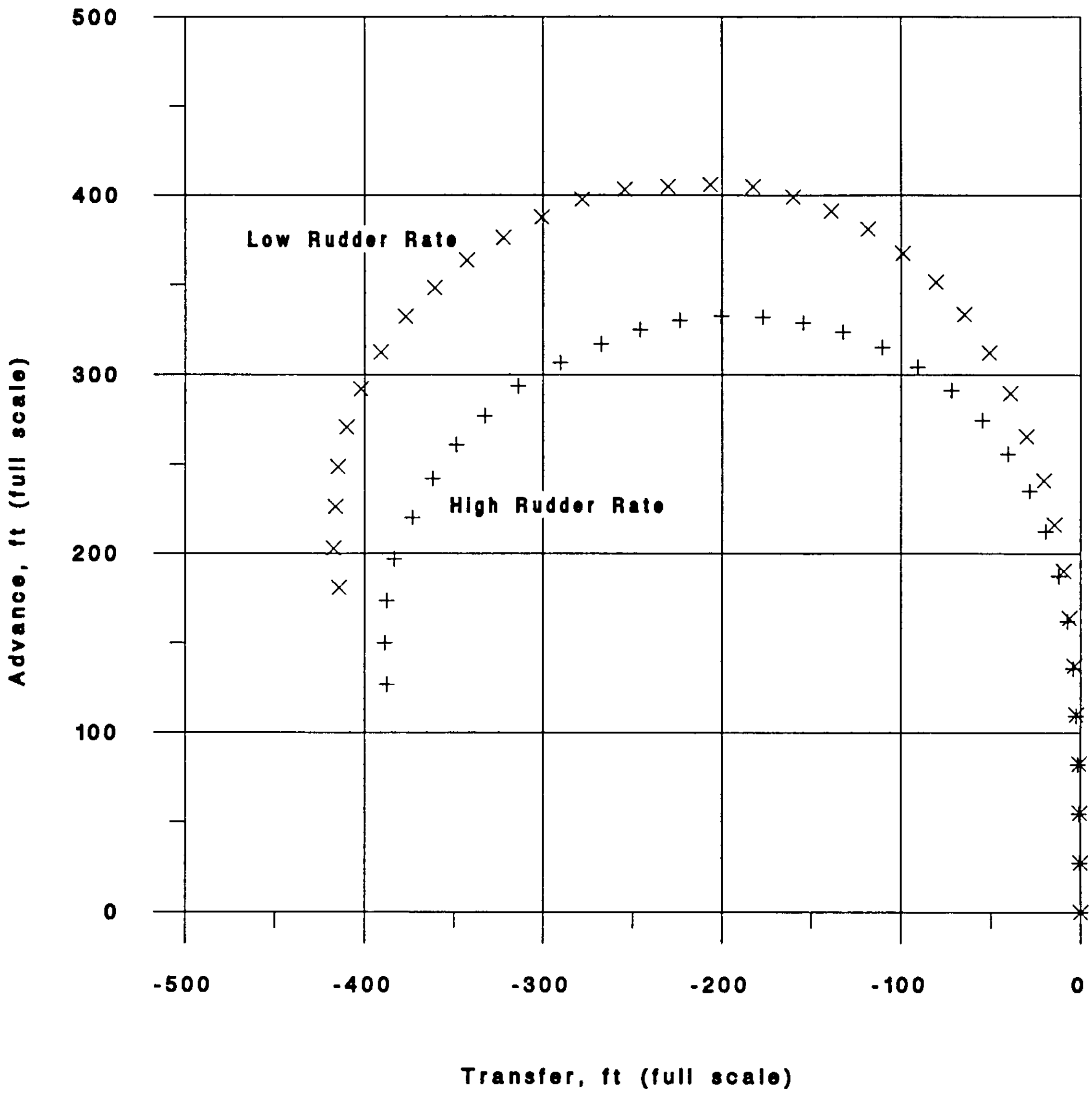
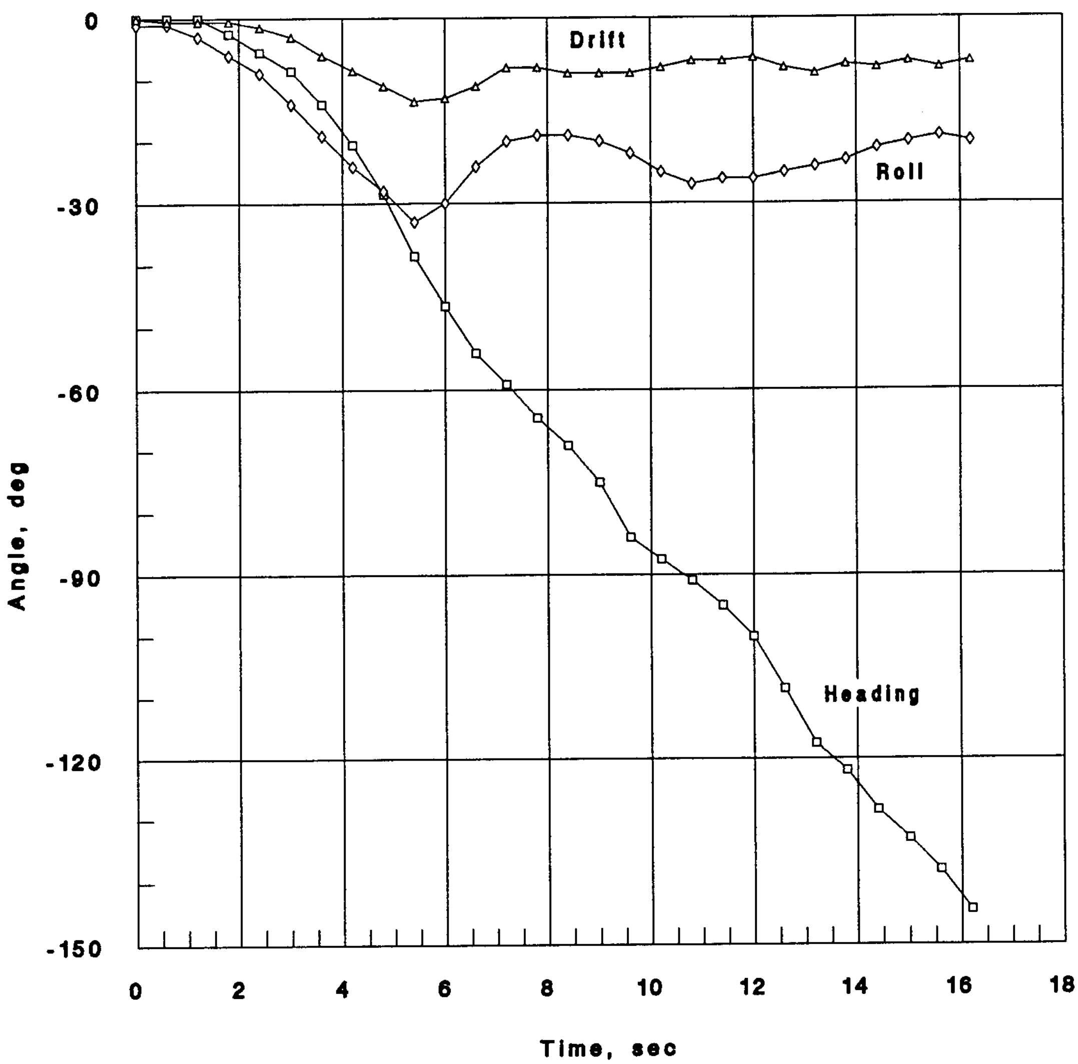
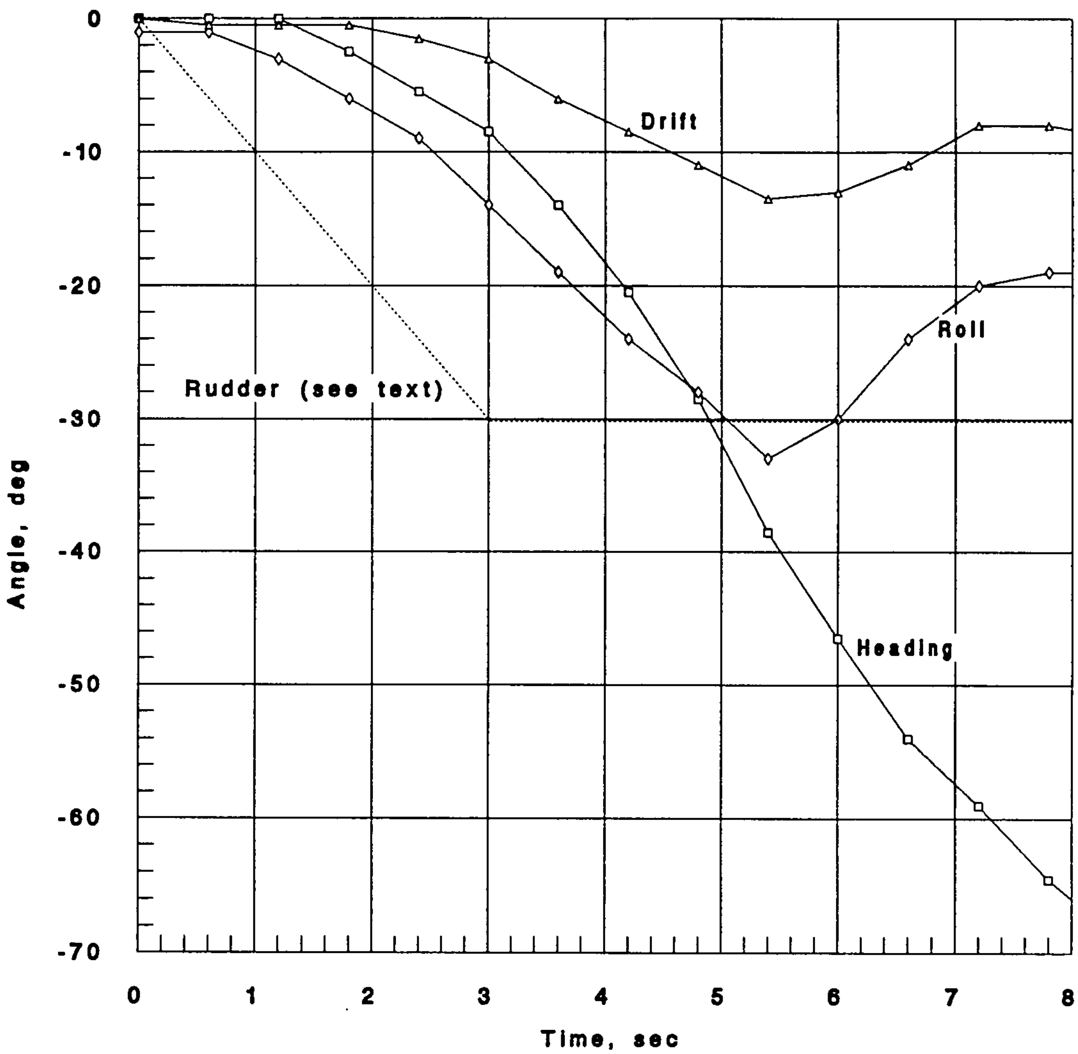


FIGURE 23 Turning Trajectory of 47 ft MLB
Approach: 27 kt Rudder: 20 deg



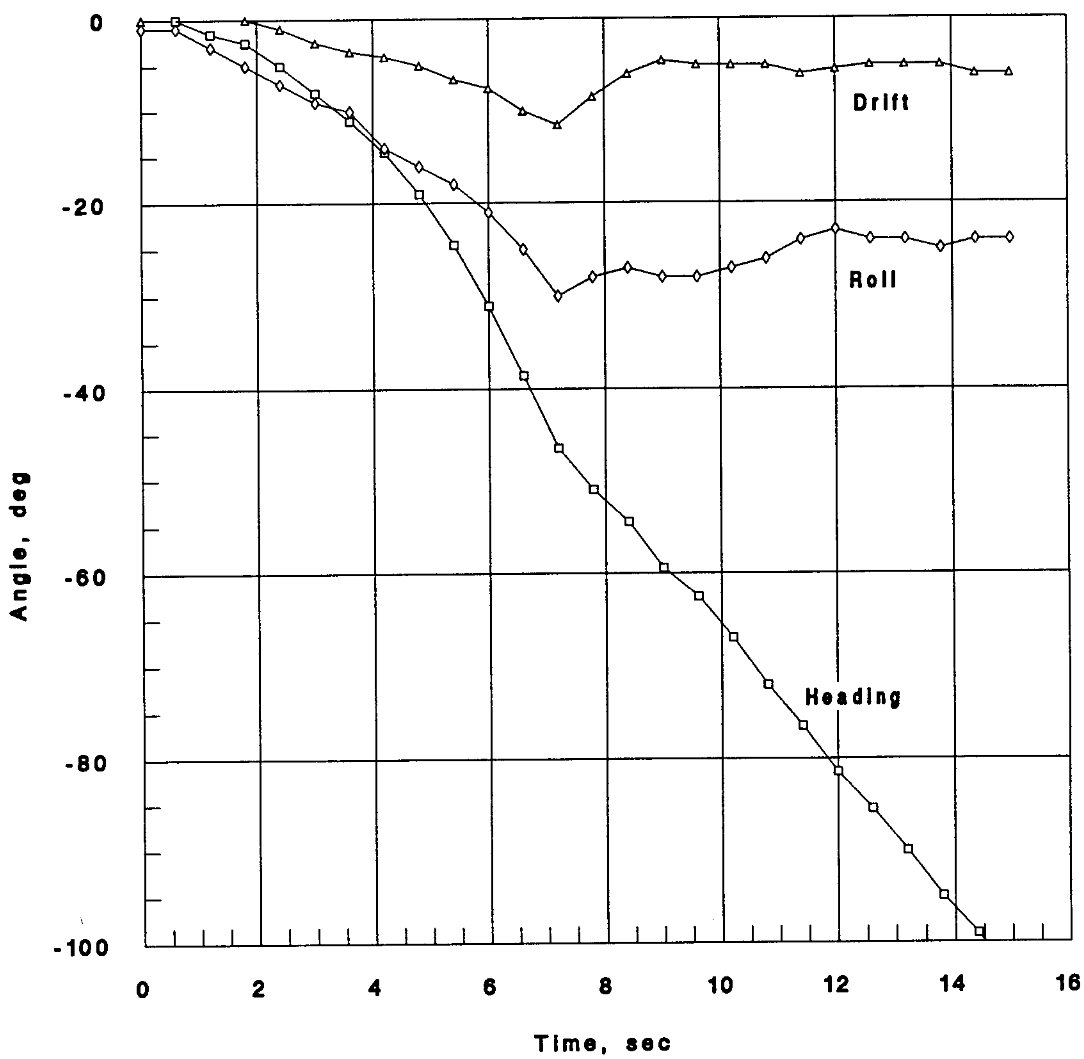
Approach: 27 kt   Rudder: 30 deg   Rate: High

FIGURE 24   Time histories of roll, drift and heading angles in a high speed turn. Full-scale units.



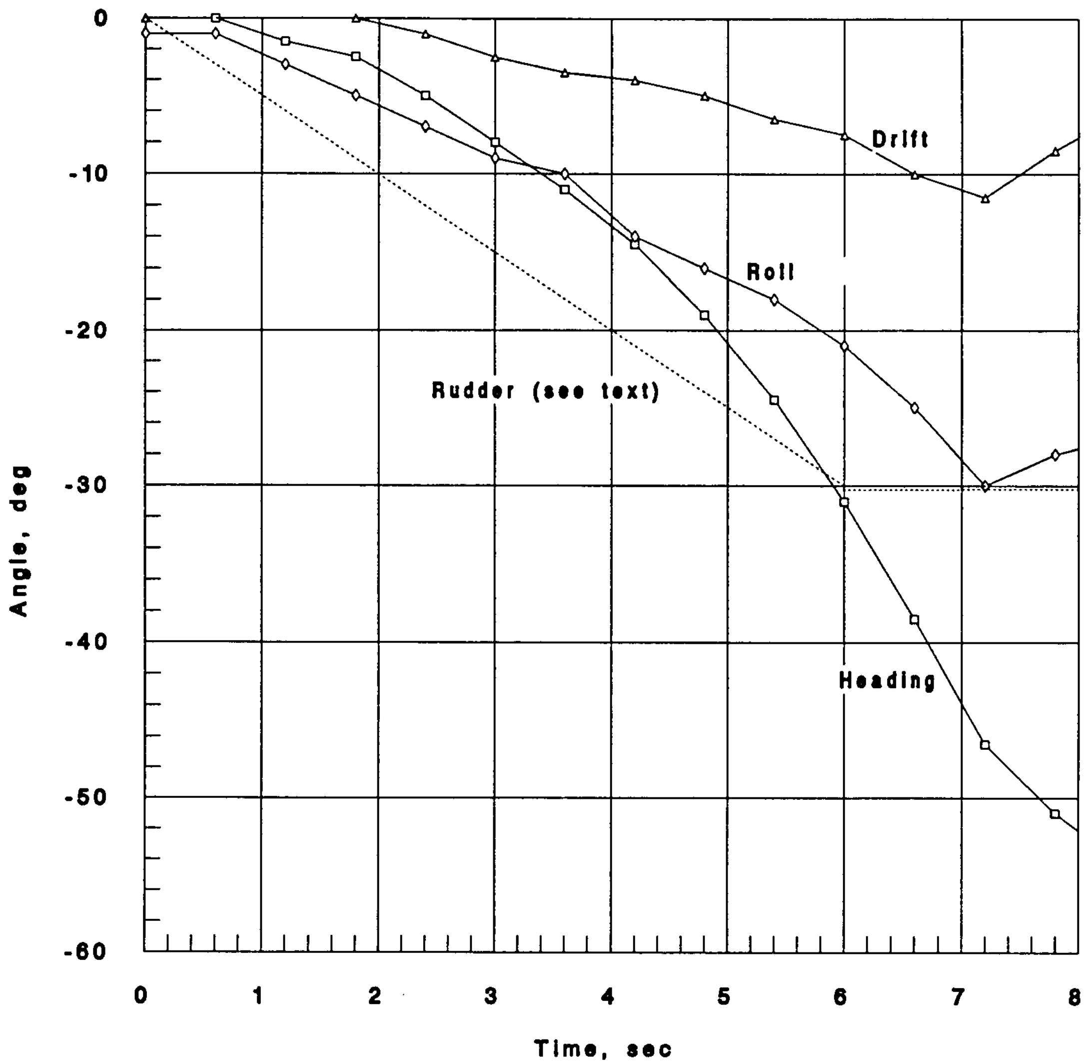
Approach: 27 kt   Rudder: 30 deg   Rate: High

FIGURE 24a Time histories of roll, drift and heading angles in the early portion of a high speed turn. Full-scale units.



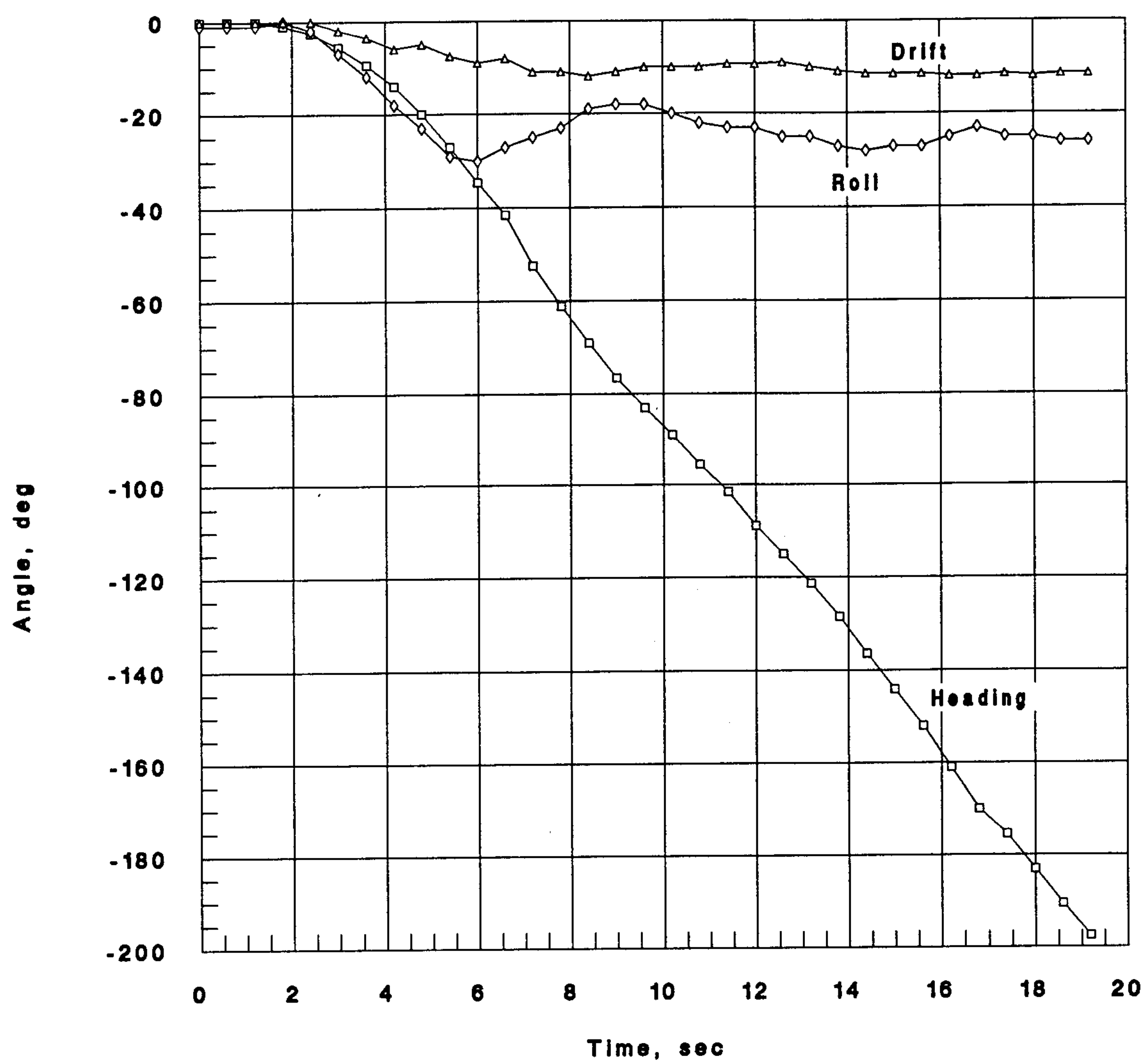
Approach: 27 kt Rudder: 30 deg Rate: Low

FIGURE 25 Time history of roll, drift and heading angles in a high speed turn. Full-scale units.



Approach: 27 kt Rudder: 30 deg Rate: Low

FIGURE 25a Time history of roll, drift and heading angles in the early portion of a high speed turn. Full-scale units.



Approach: 27 kt Rudder: 20 deg Rate: High

FIGURE 26 Time history of roll, drift and heading angles in a high speed turn (Full-scale units)

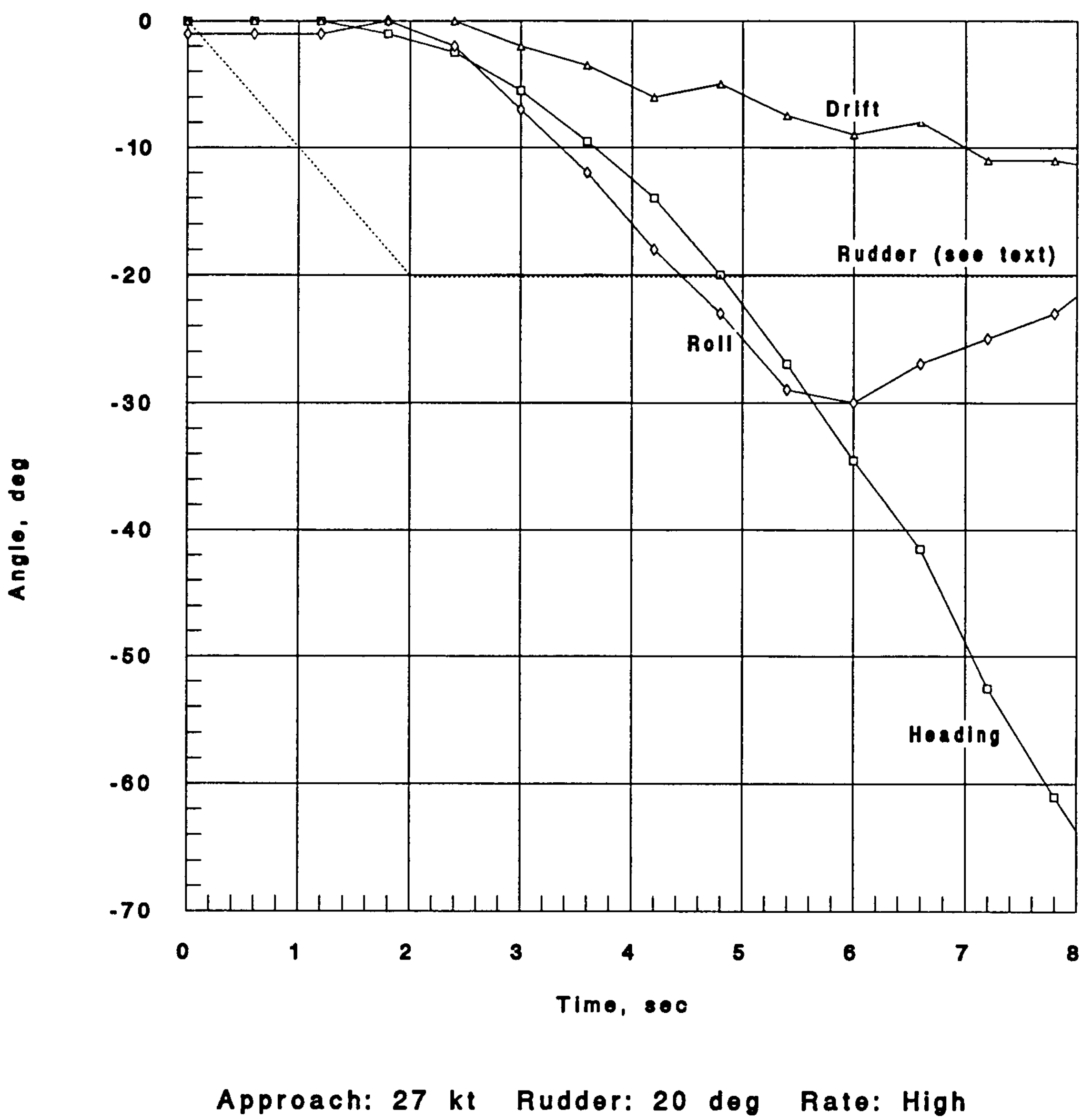
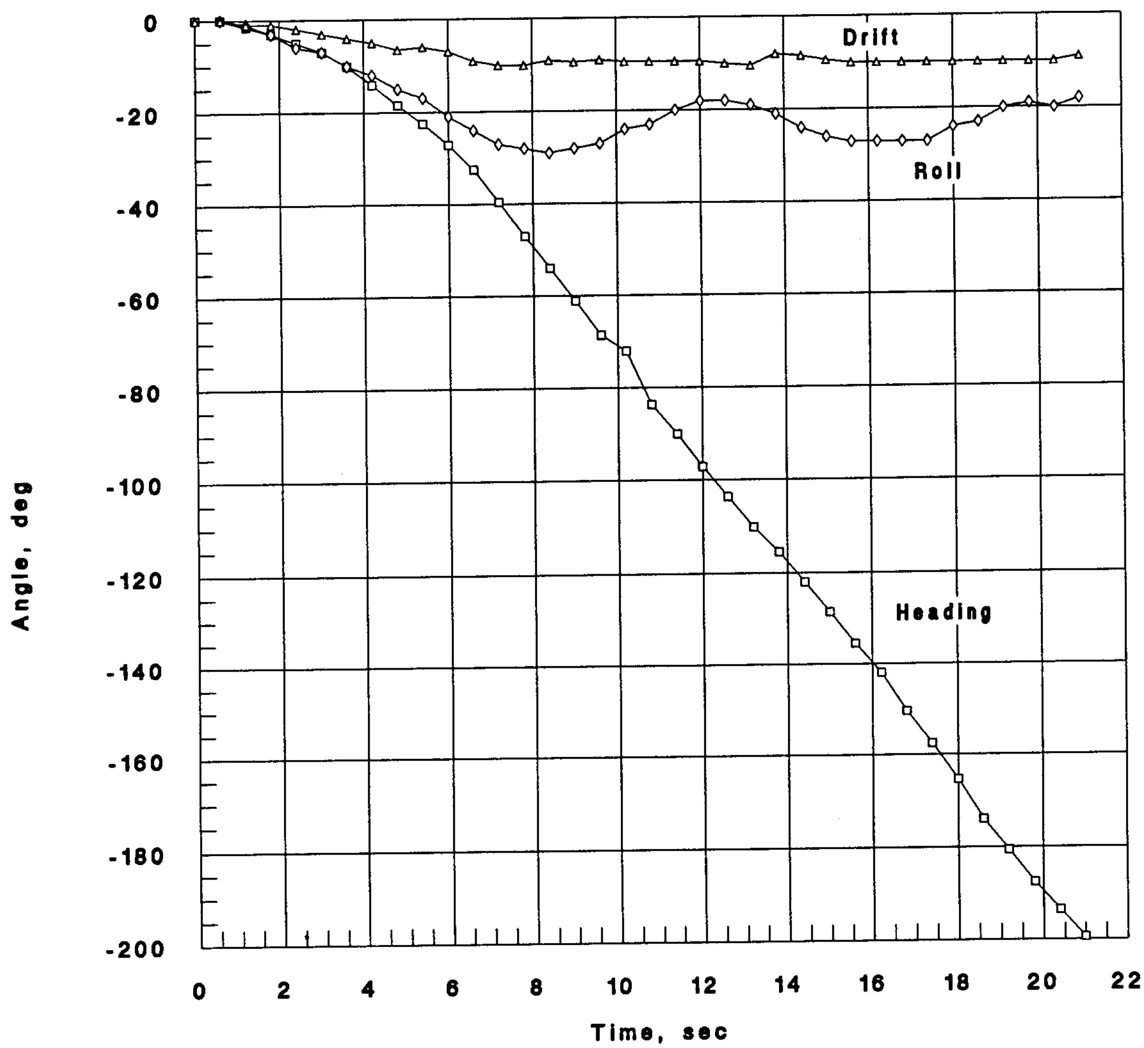
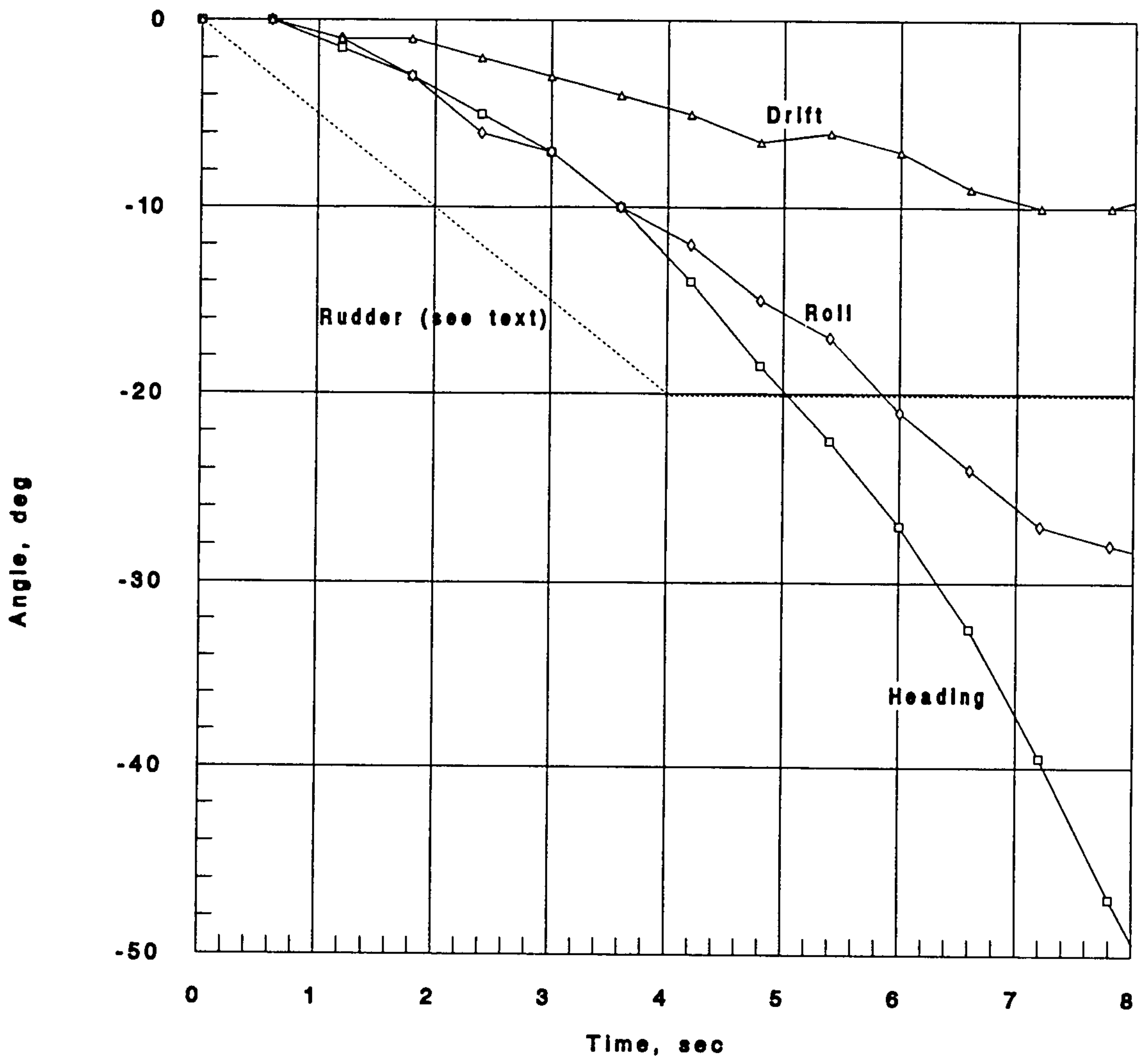


FIGURE 26a Time history of roll, drift and heading angles in the initial portion of a high speed turn (Full-scale units)



Approach: 27 kt Rudder: 20 deg Rate: Low

FIGURE 27 Time history of roll, drift and heading angles in a high speed turn. Full-scale units.



Approach: 27 kt   Rudder: 20 deg   Rate: Low

FIGURE 27a   Time history of roll, drift and heading angles in initial portion of a high speed turn. Full-scale units.

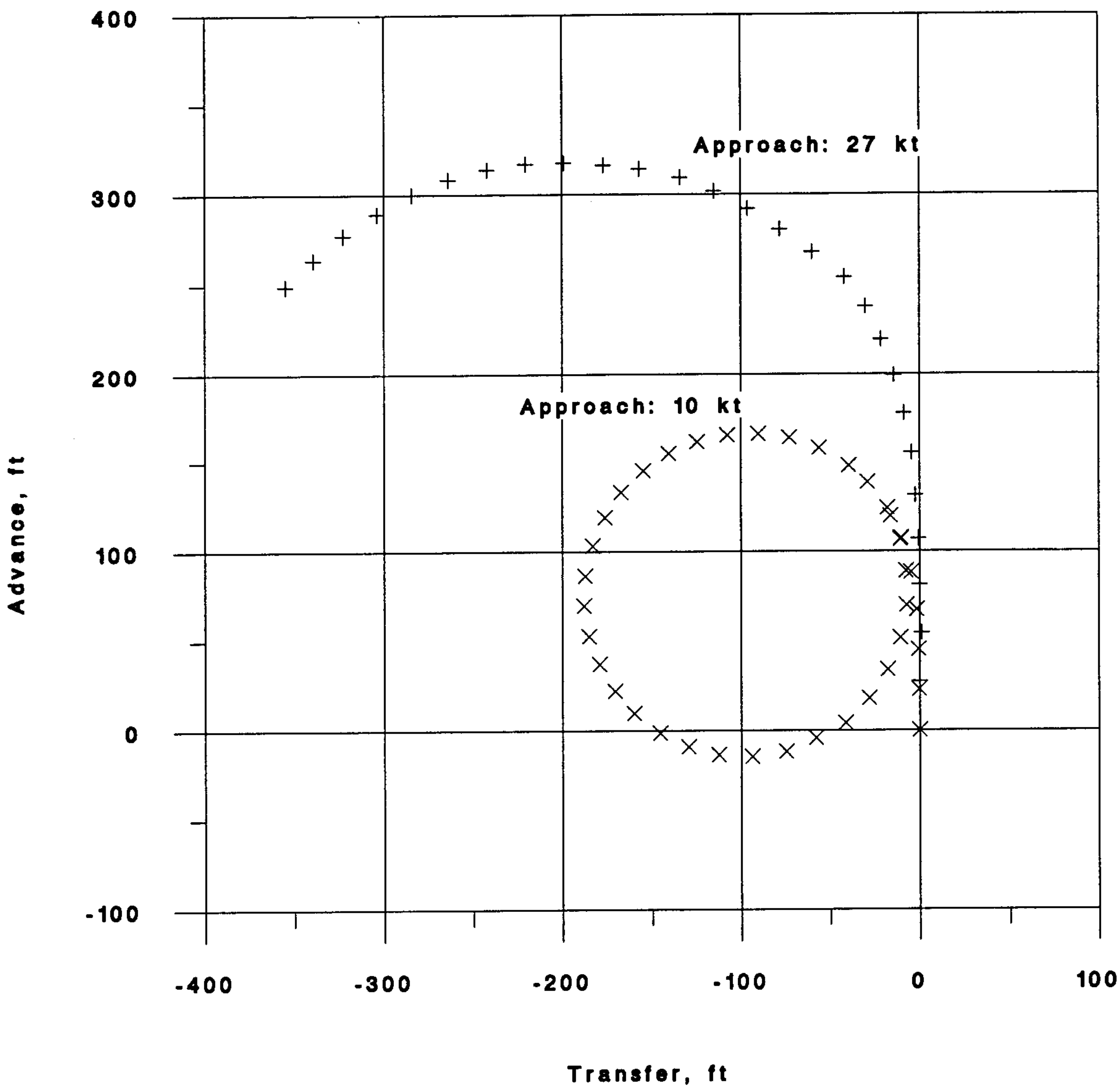


FIGURE 28 Effect of Approach Speed on Turning Trajectory; Rudder: 30 deg; Rate: High Full-scale units.

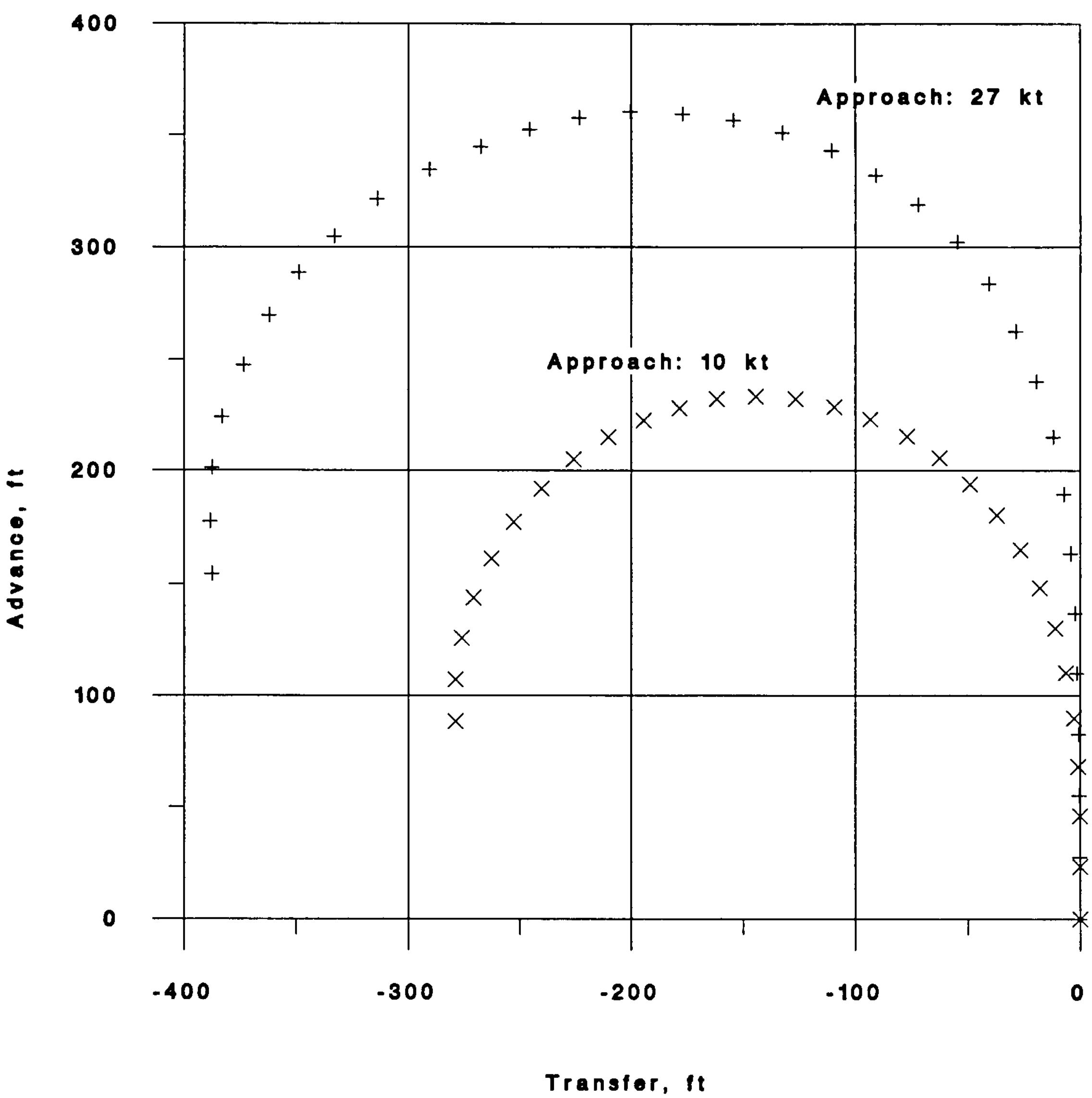


FIGURE 29 Effect of Approach Speed on Turning Trajectory; Rudder: 20 deg; Rate: High Full-scale units.

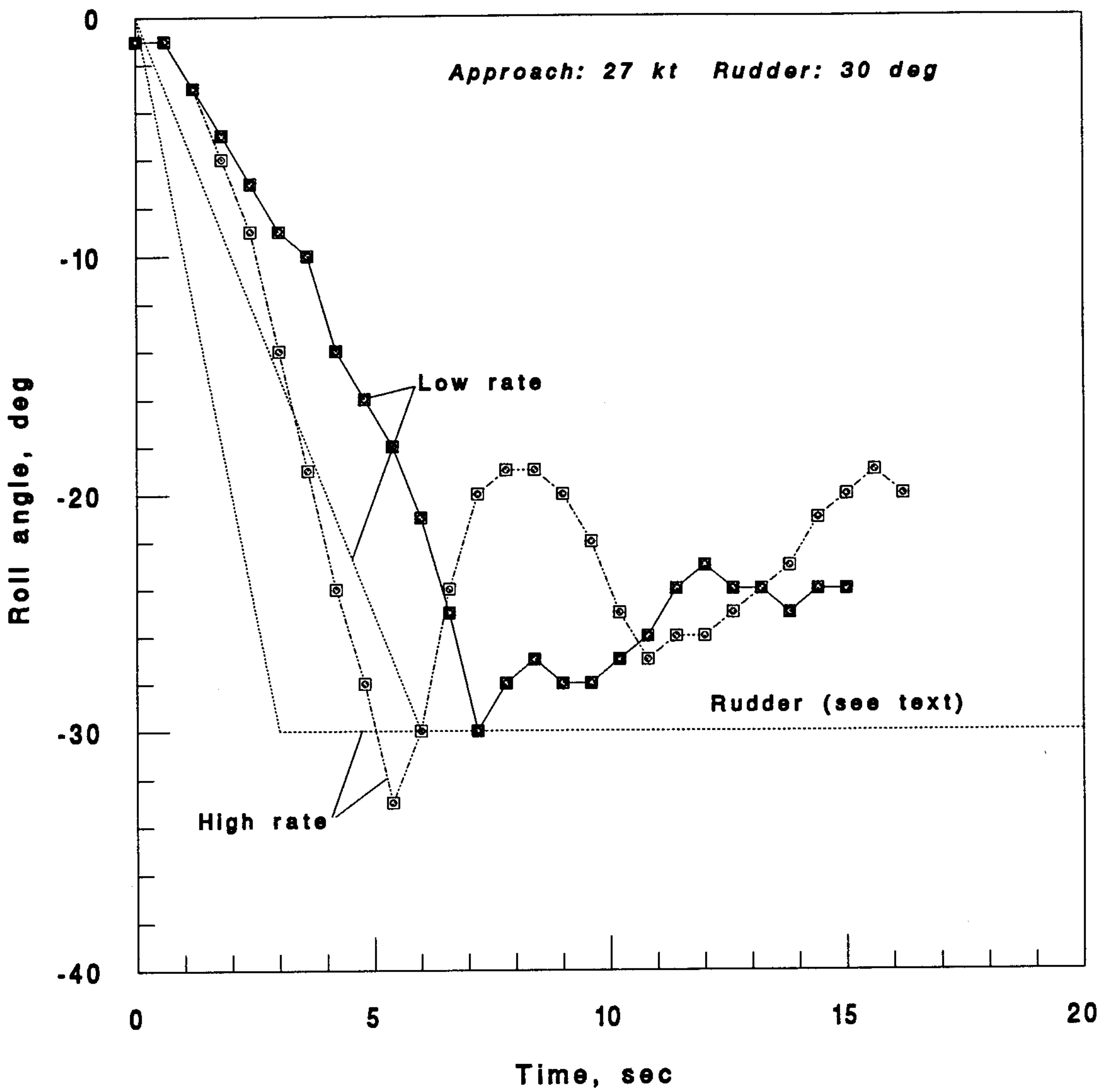


FIGURE 30 Effect of rudder rate on rolling in a turn. Full scale units.

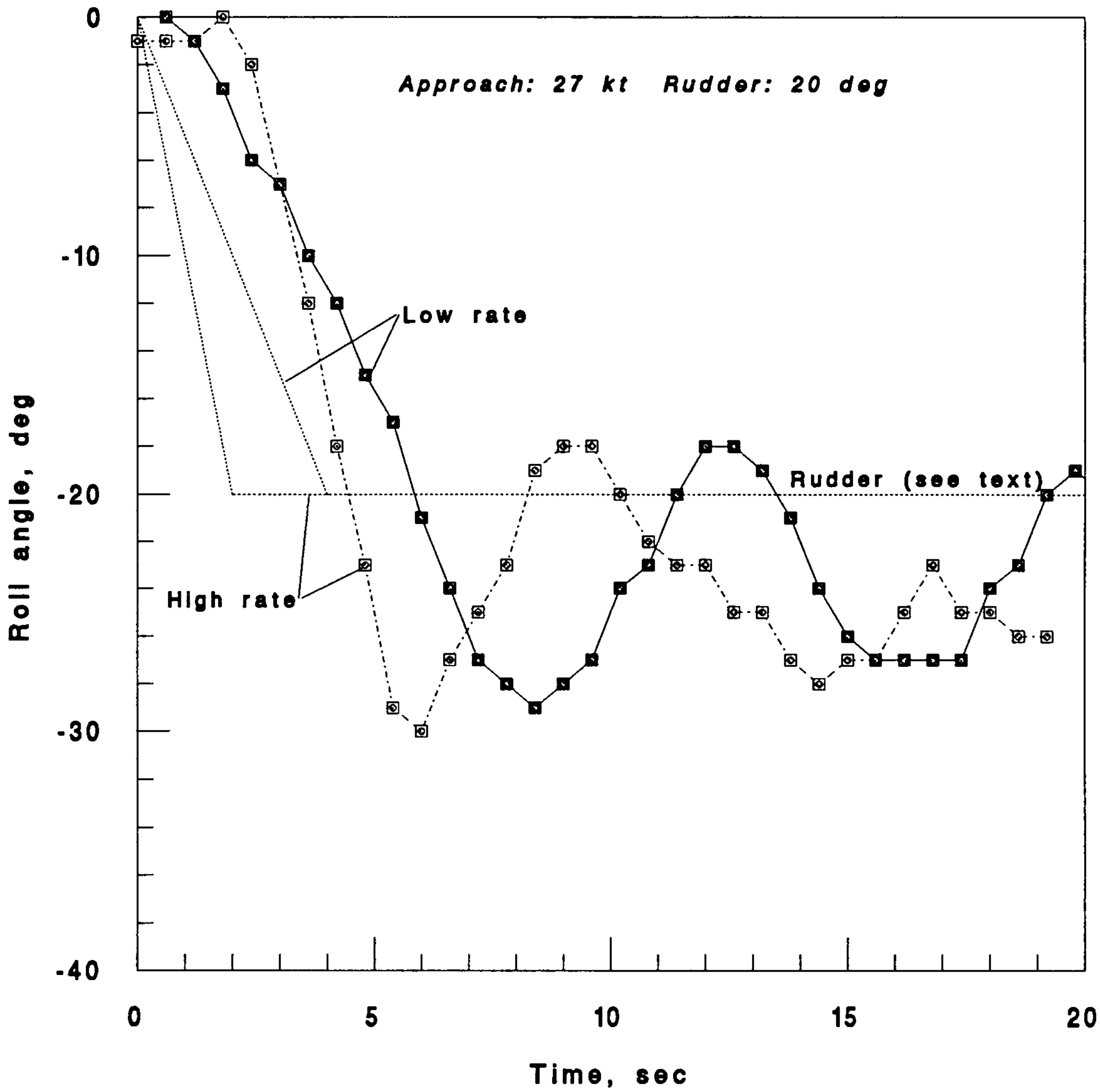


FIGURE 31 Effect of rudder rate on rolling in a turn
Full scale units.

APPENDIX A

INITIAL VELOCITY CORRECTIONS

Analysis of the trajectories from the photographs, after correction for lens distortion as described in the text, showed that in some of the photographs of the approach phase of the high-speed turns, the model was not up to speed at the initiation of the turn. This problem was restricted to the photographs obtained in the second free-running model test session; in the first session, more space was available for acceleration. Thus, only the initial points of the measured high-speed trajectories were affected (subsequent points being from previous runs which were initiated at the proper speed); fortunately, the drift, roll, heading and transfer were all small in this phase of the turns. A simple correction was applied to the trajectories as described below.

First, the x and y components of velocity were estimated from the measured trajectories as follows:

$$u = dx/dt = [x(t) - x(t-dt)]/dt$$

$$v = dy/dt = [y(t) - y(t-dt)]/dt$$

where dt is the time interval between LED pulses (0.2 sec model-scale). The velocity components were next plotted against time. Then, the curve of u(t) was extrapolated back from the points which were determined from the first set of photographs, to the proper initial velocity of 27 knots, using the shape of the measured curve as a guide (a smooth variation of u with time was assumed). The "corrected" u velocity component was then read from the extrapolated curve; the v-component was multiplied by the ratio of the corrected to the measured u-components. The trajectory was then recomputed using the new velocity components.

Figure A1 shows the original and corrected velocity components in a typical case. It can be seen that there are also some discontinuities in the velocity curves where two photographs were joined; these were also smoothed in the correction process as shown. Figure A2 shows the measured and corrected trajectories in this case.

As mentioned in the text, the measured trajectories at an approach speed of 27 knots and a rudder deflection of 30 degrees ended before the heading changed 180 degrees. To estimate the tactical diameter in these cases, the trajectories were extrapolated by assuming that a constant speed and rate of change of heading had been reached at the end of the measured trajectories. The results are shown on Figures A3 and A4.

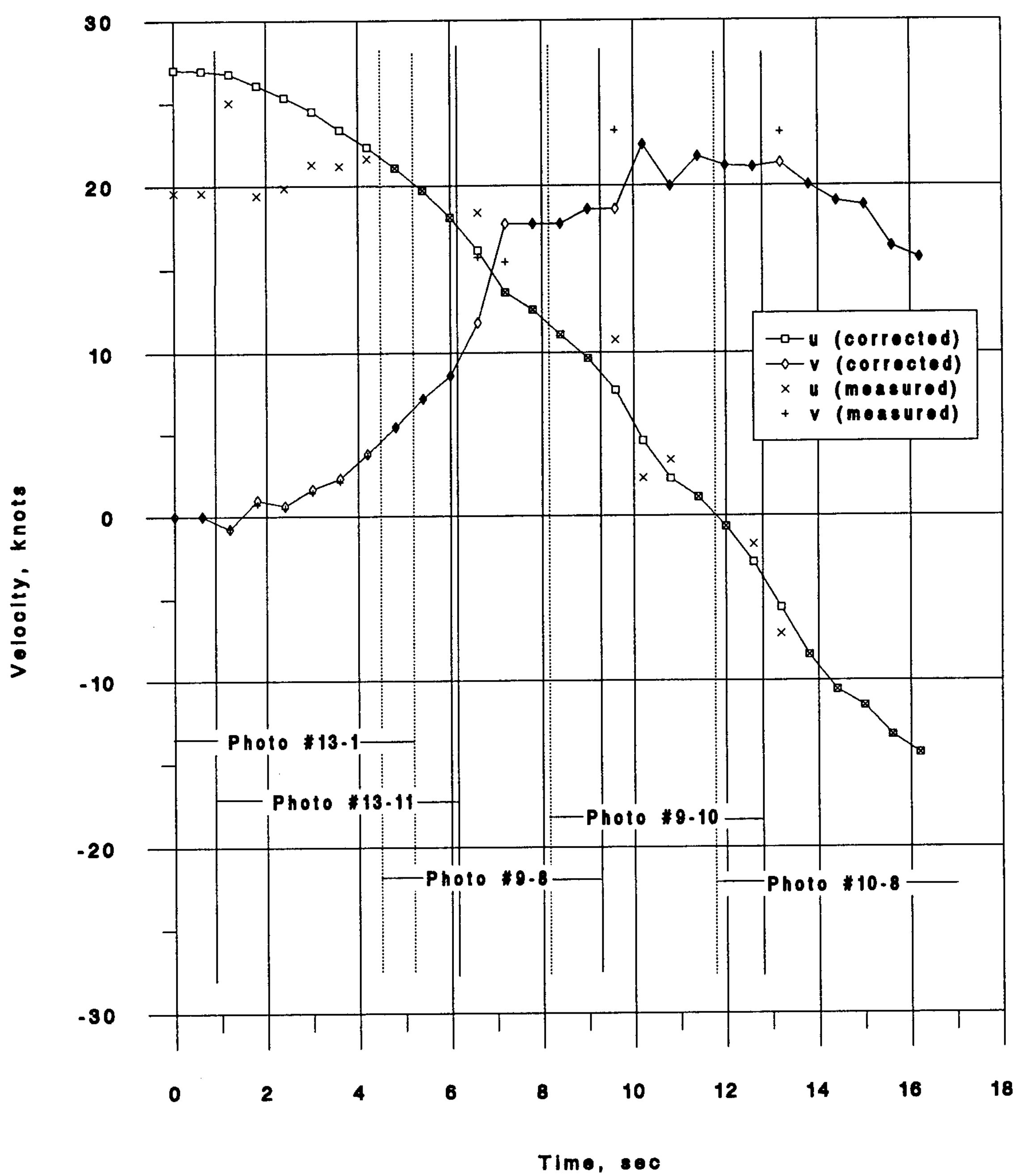


Figure A1 Comparison of measured and corrected velocity components. Approach: 27 kt; Rudder: 30 deg; Rudder rate: High

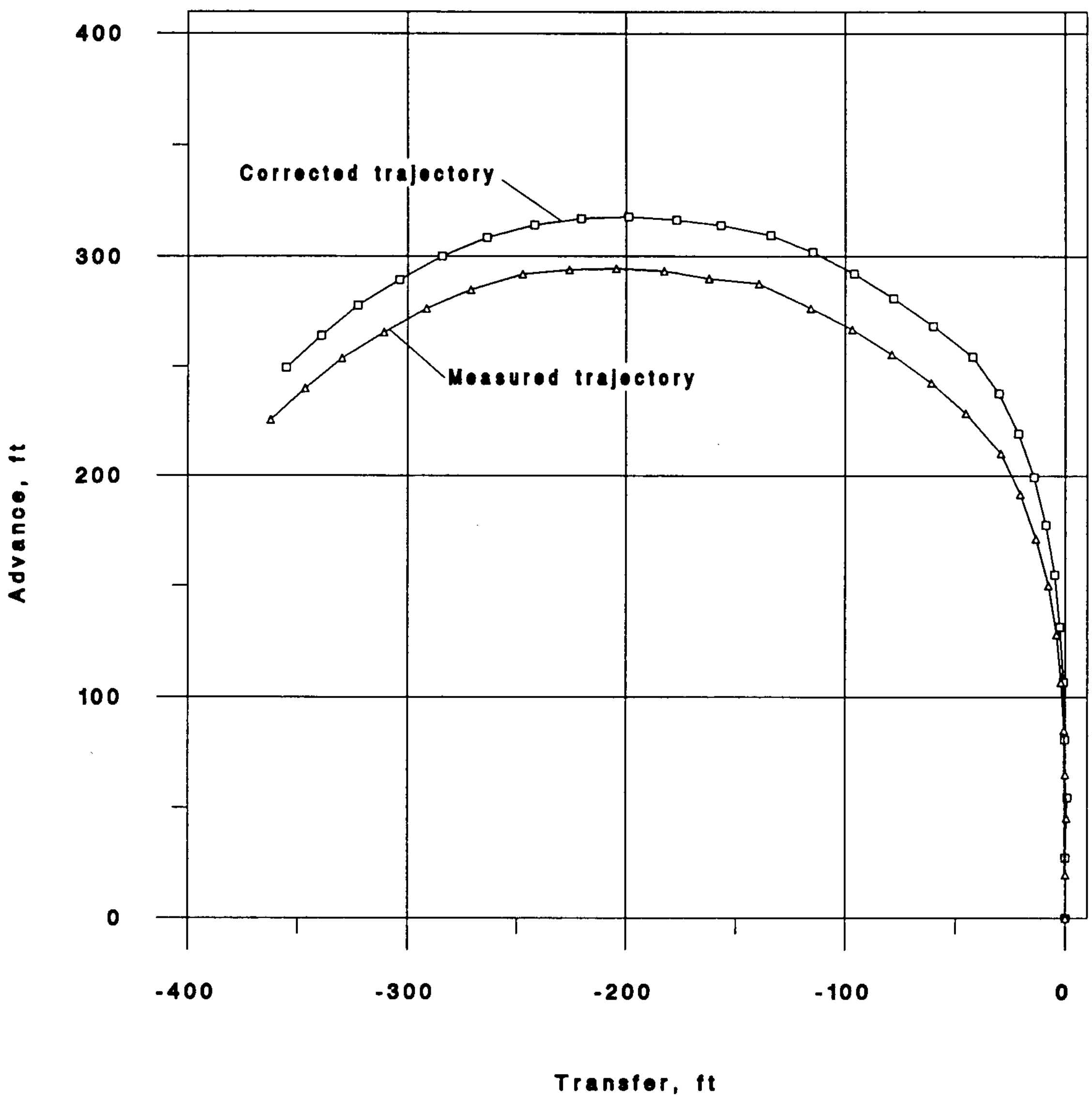


Figure A2 Effect of velocity correction on trajectory. Approach: 27 kt; Rudder: 30 deg; Rudder rate: High

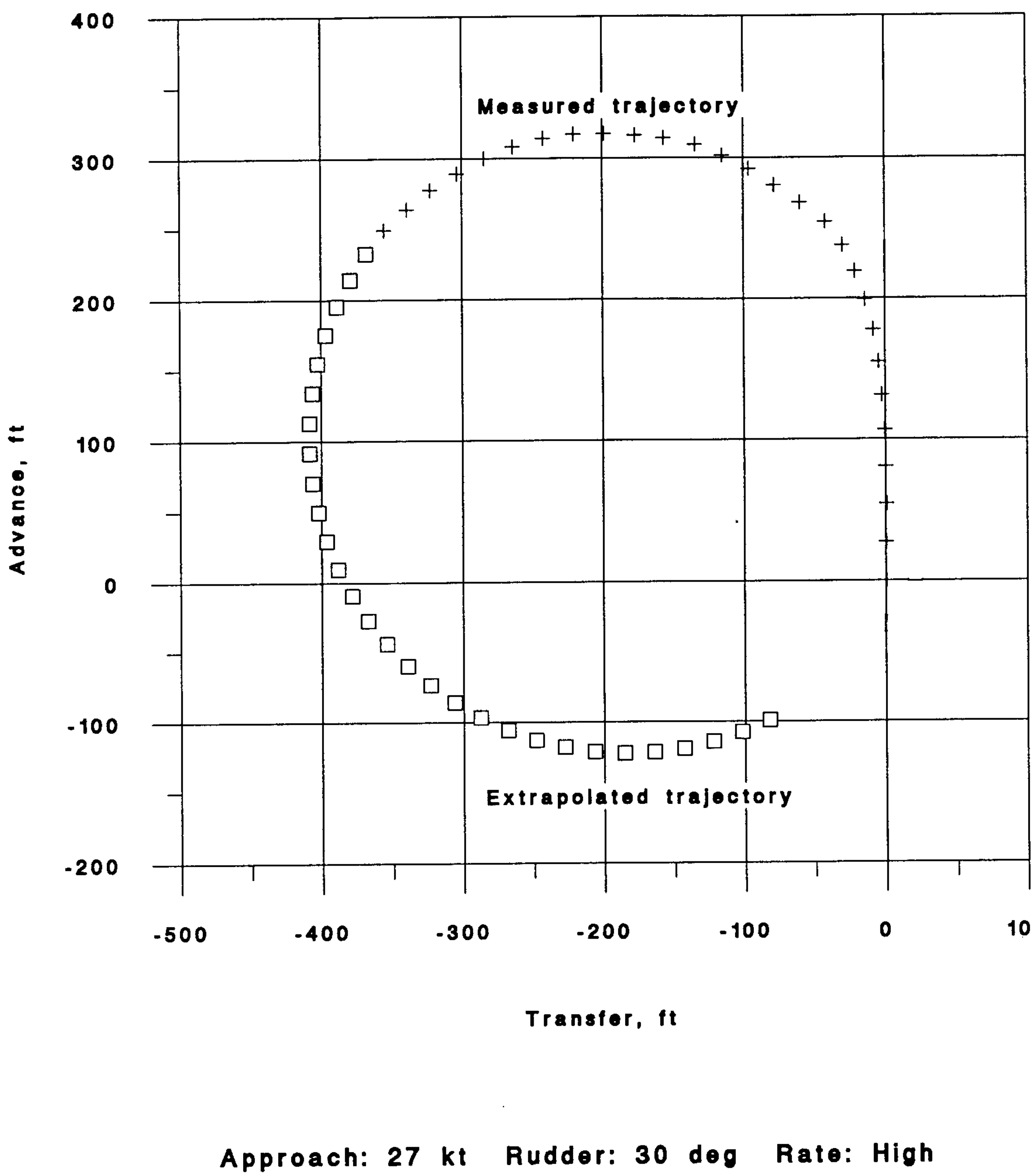


FIGURE A3 Extrapolated trajectory

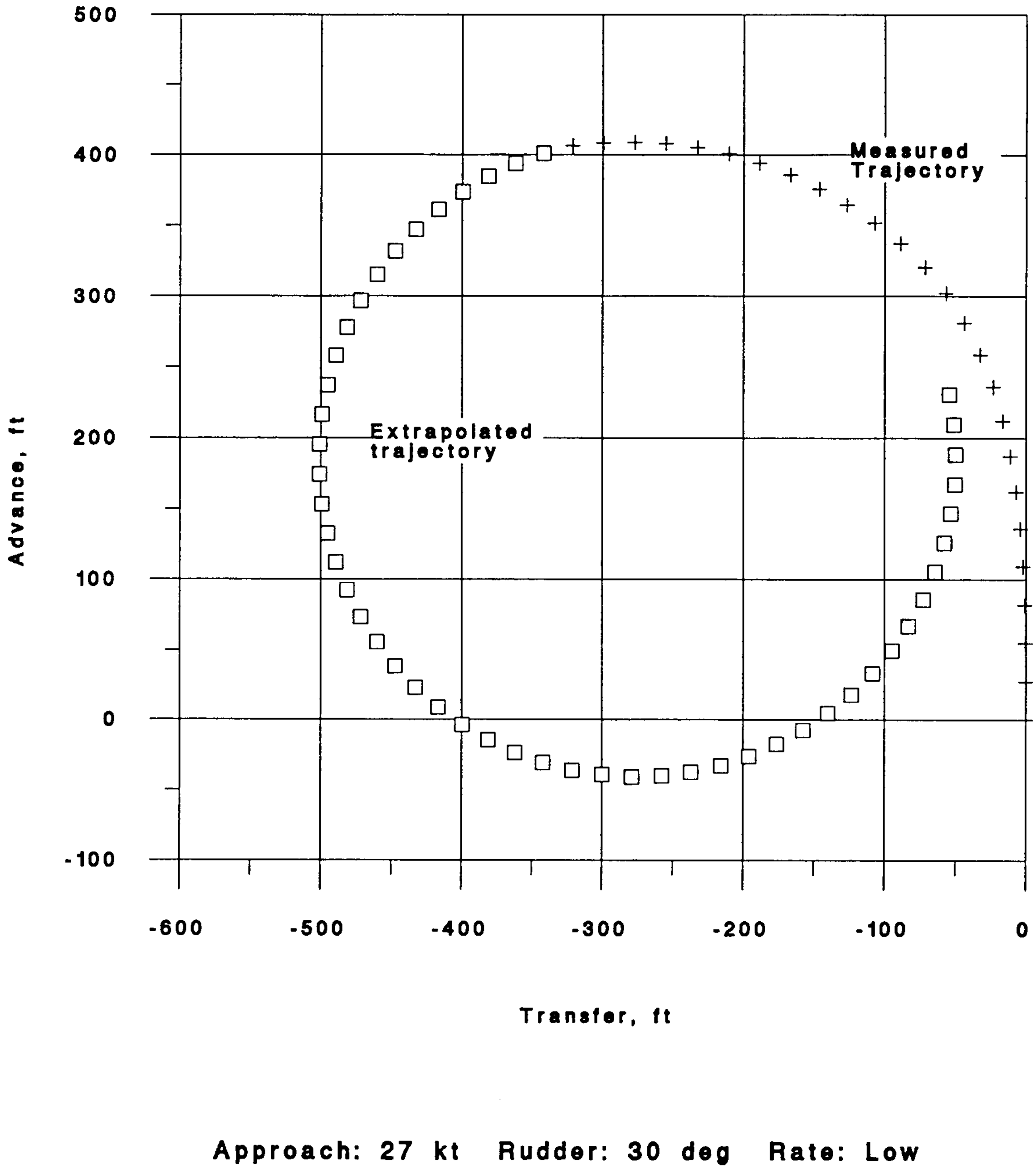


FIGURE A4 Extrapolated trajectory